

ILC Physics

Sven Heinemeyer, IFCA (CSIC – UC)

Santander, 07/2006

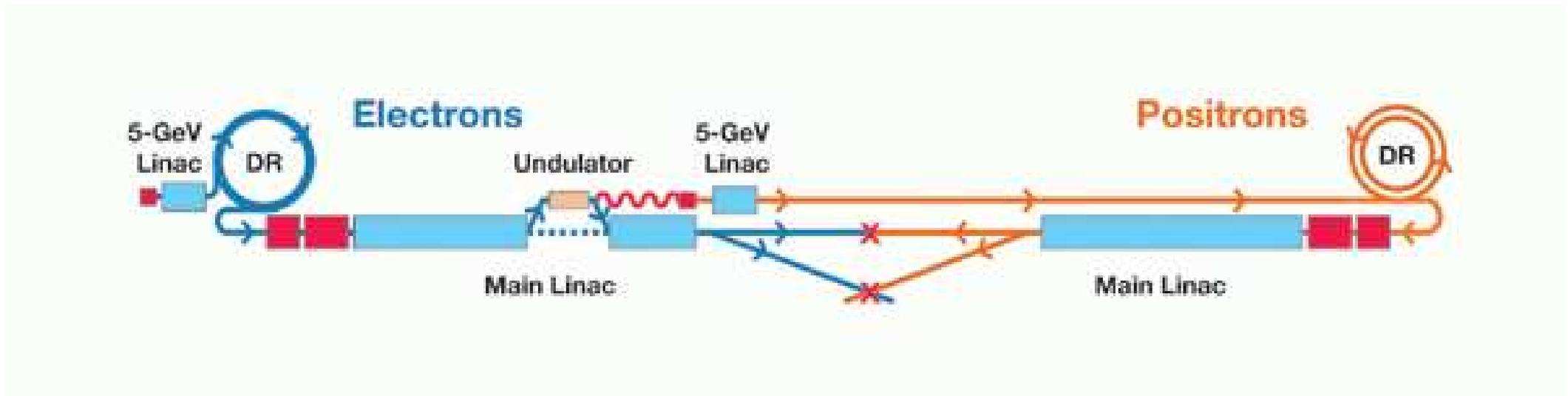
1. The International Linear Collider (ILC)
2. Short introduction to Higgs and SUSY
3. Top physics (and electroweak precision observables) at the ILC
4. Higgs physics at the ILC
5. Supersymmetry at the ILC
6. Conclusions

1. The International Linear Collider (ILC)

Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV

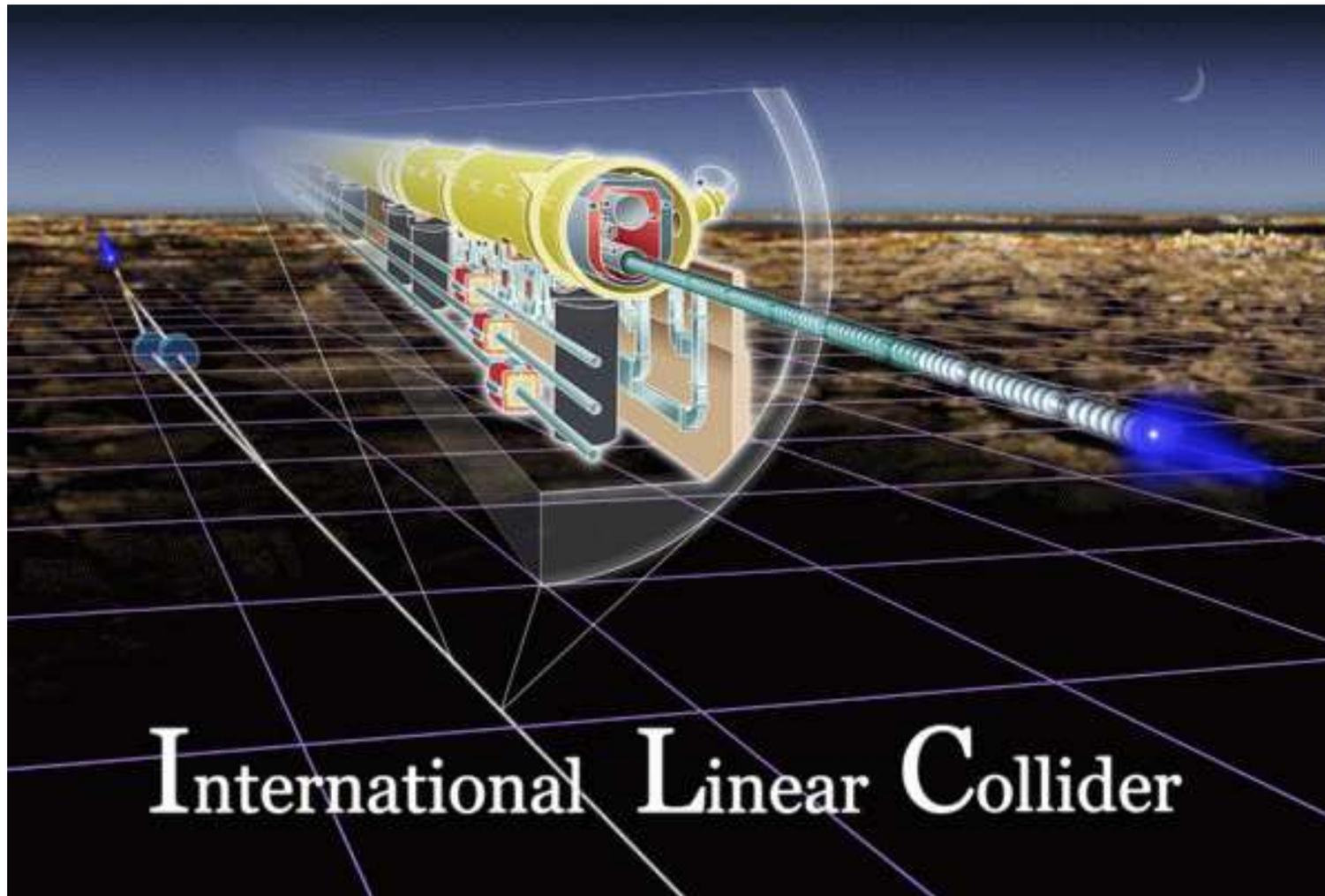
based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



- 2 interaction regions (one without(?), one with crossing angle)
- undulator based e^+ source
- polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

The tunnel and the tubes:



Possible sites: Fermilab, KEK, CERN, Dubna, DESY



The state who pays most will get it . . .

Anticipated decision: 2009(?), start digging: 2010(?)

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⇒ start with physics: 2015(?) (most optimistic scenario)

Other options:

- GigaZ:
running with high luminosity at low energies (Z pole, WW threshold)
- e^-e^- :
produce doubly charged particles in the s channel
- $e^-\gamma$:
use one e^- beam to produce high-energy photons
produce charged particles in the s channel
- $\gamma\gamma$:
use both beams to produce high-energy photons
(e.g. heavy Higgs production in the s channel)

Physics at the ILC

Reality: ILC will start after the LHC

Q: What will the ILC add to the LHC?

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A: The ILC will add **precision** \Rightarrow The ILC delivers \oplus needs precision!

The ILC can make **discoveries** \Rightarrow What can the ILC detect/discover?

Physics at the ILC

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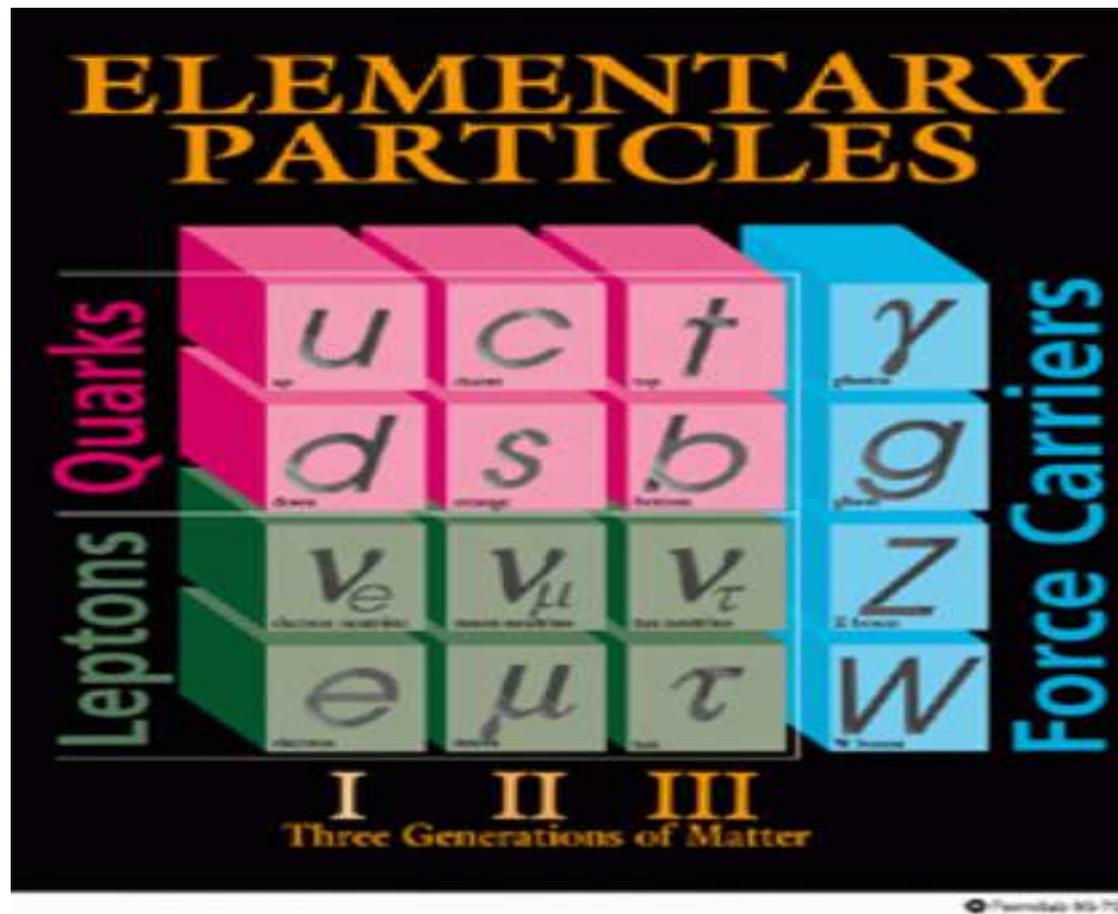
The ILC can make **discoveries** \Rightarrow What can the ILC detect/discover?

Several physics aspects:

- Top/electroweak precision observables
- QCD
- Higgs (SM and (mostly) beyond)
- Supersymmetry (SUSY)
- Extra dimensions, KK towers
- Strong electroweak symmetry breaking

2. Short introduction to Higgs and SUSY

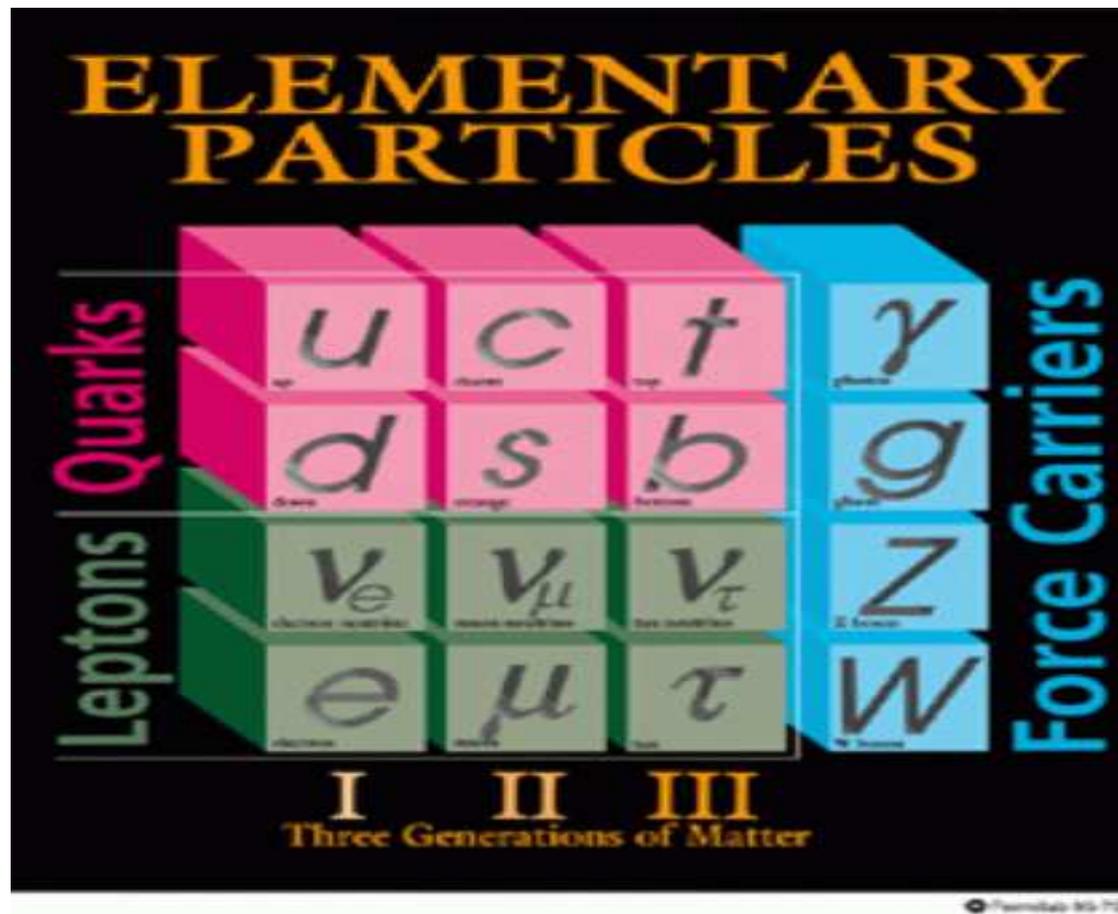
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⇒ all particles experimentally seen

2. Short introduction to Higgs and SUSY

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

⇒ but one particle is missing . . .

Problem:

Gauge fields Z , W^+ , W^- are **massive**

explicite mass terms in the Lagrangian \Leftrightarrow breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

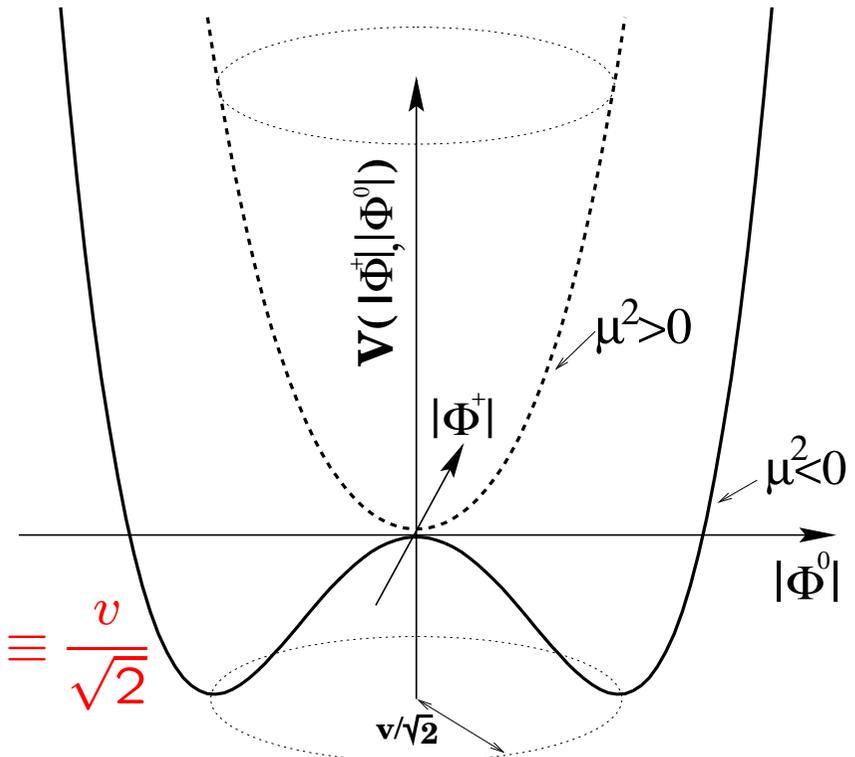
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 |\Phi^\dagger \Phi| + \lambda |\Phi^\dagger \Phi|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (\text{unitary gauge})$$

H : elementary scalar field, Higgs boson

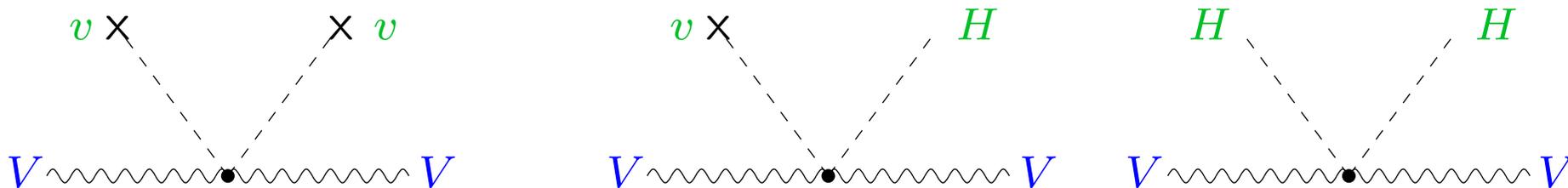
Lagrange density:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

Gauge invariant coupling to gauge fields

\Rightarrow mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:

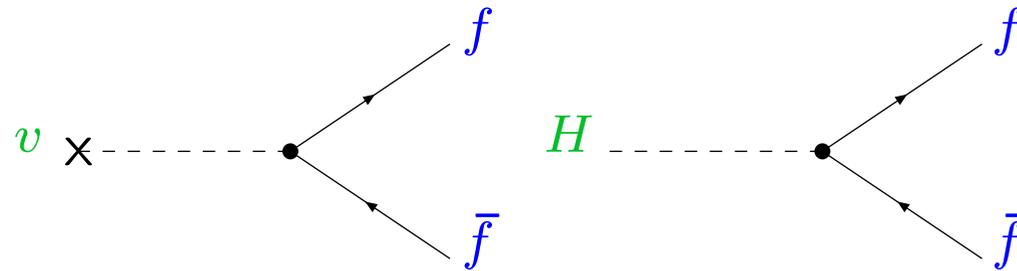


\Rightarrow VV mass terms

\Rightarrow triple/quartic couplings to gauge bosons

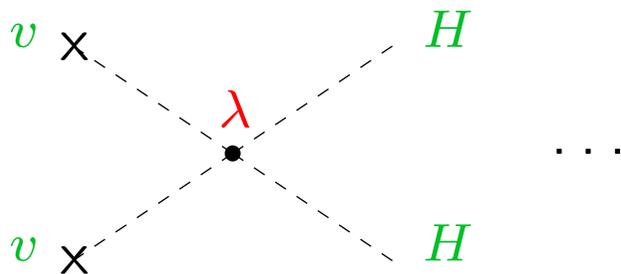
$$g_2^2 v^2 / 2 \equiv M_W^2, \quad (g_1^2 + g_2^2) v^2 / 2 \equiv M_Z^2 \quad \Rightarrow \text{coupling} \propto \text{masses}$$

2.) fermion mass terms: Yukawa couplings



$$m_f = v g_f \Rightarrow \text{coupling} \propto \text{masses}$$

3.) mass of the Higgs boson: self coupling



$$\lambda = M_H^2/v$$

$$M_H = v\sqrt{\lambda} \quad \text{free parameter}$$

→ last unknown parameter of the SM

⇒ establish Higgs mechanism \equiv find the Higgs \oplus measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \rightarrow W_L W_L$

$$\mathcal{M}_V = \text{[diagram 1]} + \text{[diagram 2]} + \text{[diagram 3]} = -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1) \quad \text{for } E \rightarrow \infty$$

The diagrams show the tree-level scattering of two longitudinal W bosons into two longitudinal W bosons. The first diagram is a t-channel exchange of a photon or Z boson. The second diagram is a s-channel exchange of a photon or Z boson. The third diagram is a four-point contact interaction. The result is a term that grows with energy, indicating a violation of unitarity.

⇒ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$$\mathcal{M}_S = \text{[diagram 4]} + \text{[diagram 5]} = g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1) \quad \text{for } E \rightarrow \infty$$

The diagrams show the tree-level scattering of two longitudinal W bosons into two longitudinal W bosons mediated by a scalar particle H. The first diagram is a t-channel exchange of H, and the second is a s-channel exchange of H. The result is a term that also grows with energy, but with a positive sign, which can compensate for the negative term from the vector boson exchange.

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4} (g_{WWH}^2 - g^2 M_W^2) + \dots$$

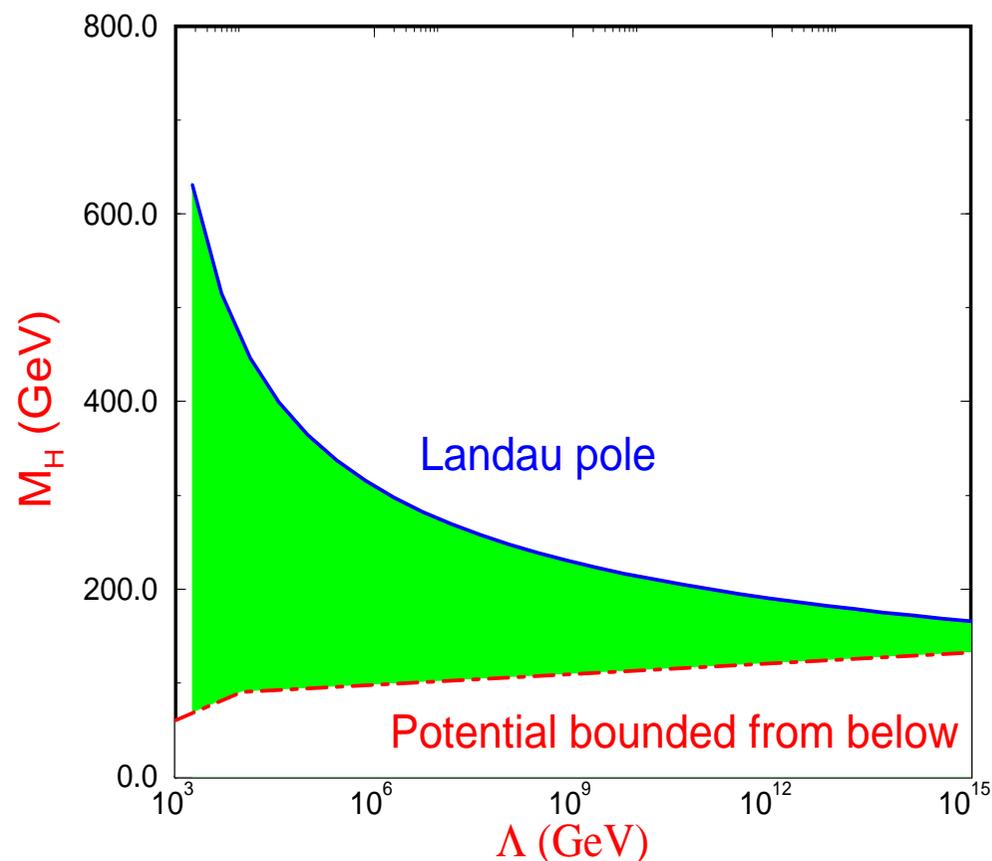
⇒ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g M_W$$

What else do we know about the Higgs boson?

SM at high energies

- upper limit on M_H :
 - dependence of coupling
 - λ_{HHHH} from energy scale Λ
 - ⇒ divergence: Landau pole
- lower limit on M_H :
 - stability of the vacuum :
 - $V(v) < V(0)$
 - [Coleman, Weinberg '73]
- combined ⇒

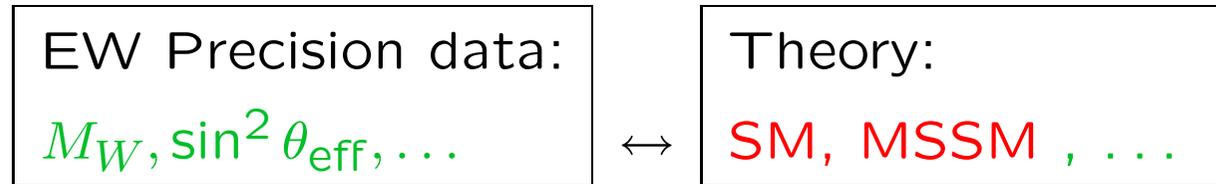


Λ : scale up to which the SM is valid

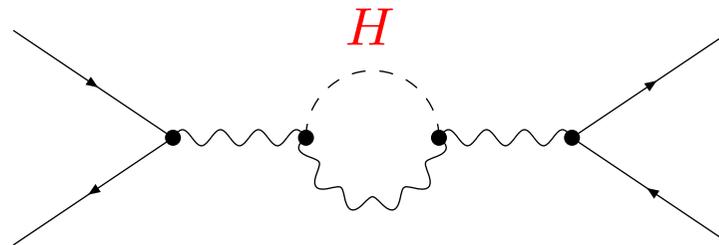
$$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$$

Indirect measurements via precision observables (POs):

Comparison of electro-weak precision observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections



All parameters of the model enter
limits on M_H

Global fit to all SM data:

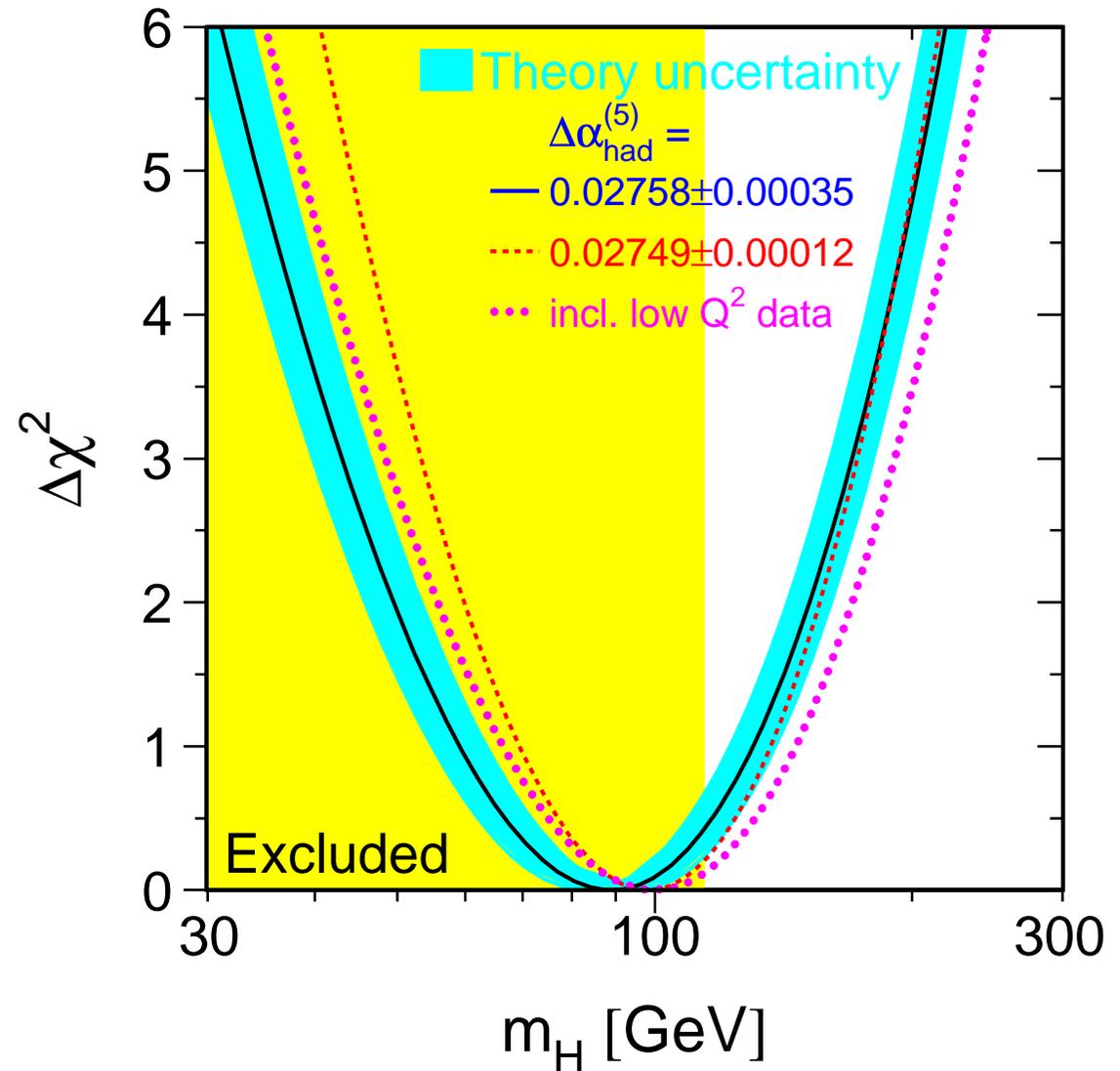
[LEPEWWG '06]

$$\Rightarrow M_H = 89_{-30}^{+42} \text{ GeV}$$

$$M_H < 175 \text{ GeV, 95\% C.L.}$$

Assumption for the fit:
SM incl. Higgs boson

\Rightarrow no confirmation of
Higgs mechanism



\Rightarrow Higgs boson seems to be light, $M_H \lesssim 200 \text{ GeV}$

Motivation for SUSY

Supersymmetry (SUSY) : Symmetry between

$$\begin{aligned} & \text{Bosons} \leftrightarrow \text{Fermions} \\ Q \text{ } | \text{Fermion} \rangle & \rightarrow | \text{Boson} \rangle \\ Q \text{ } | \text{Boson} \rangle & \rightarrow | \text{Fermion} \rangle \end{aligned}$$

Simplified examples:

$$\begin{aligned} Q \text{ } | \text{top, } t \rangle & \rightarrow | \text{scalar top, } \tilde{t} \rangle \\ Q \text{ } | \text{gluon, } g \rangle & \rightarrow | \text{gluino, } \tilde{g} \rangle \end{aligned}$$

⇒ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}} \Rightarrow$ SUSY is broken ...

... via **soft SUSY-breaking terms** in the Lagrangian

SUSY particles are made heavy: $M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})$

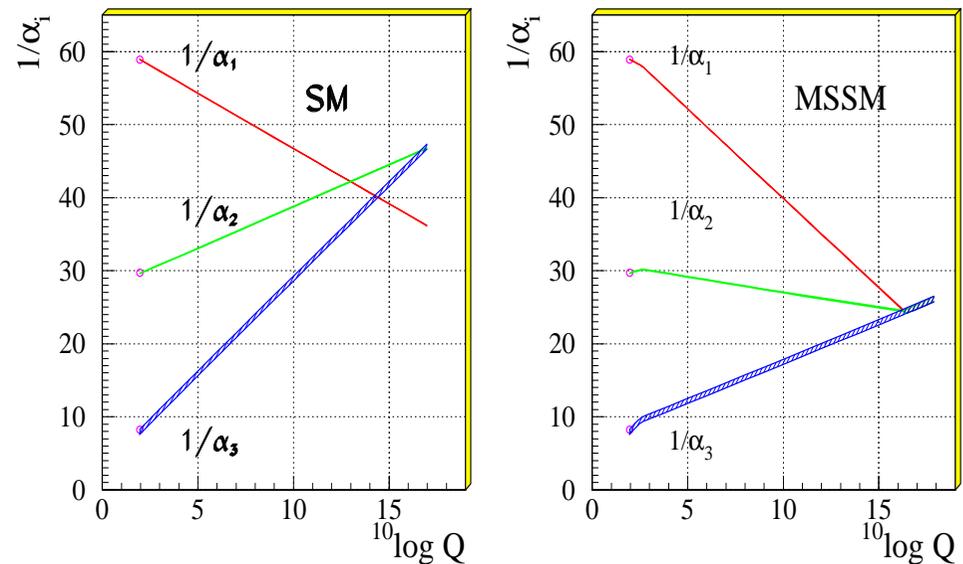
Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

- 1.) Stability of the Higgs mass against higher-order corr.
- 2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)
- 3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs
- 4.) SUSY provides CDM candidate
- 5.) ...

Unification of the Coupling Constants in the SM and the minimal MSSM



[Amaldi, de Boer, Fürstenaу '92]

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\begin{array}{llll} [u, d, c, s, t, b]_{L,R} & [e, \mu, \tau]_{L,R} & [\nu_{e,\mu,\tau}]_L & \text{Spin } \frac{1}{2} \\ [\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} & [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} & [\tilde{\nu}_{e,\mu,\tau}]_L & \text{Spin } 0 \\ g & \underbrace{W^\pm, H^\pm}_{\text{Spin } 1} & \underbrace{\gamma, Z, H_1^0, H_2^0}_{\text{Spin } 0} & \text{Spin } 1 / \text{Spin } 0 \\ \tilde{g} & \tilde{\chi}_{1,2}^\pm & \tilde{\chi}_{1,2,3,4}^0 & \text{Spin } \frac{1}{2} \end{array}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

→ CPV will be neglected throughout this talk!

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

physical states: h^0, H^0, A^0, H^\pm

Goldstone bosons: G^0, G^\pm

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta)$$

Predict all Higgs masses in terms of M_A and $\tan\beta$ (and radiative corrections):

Contrary to the SM:

m_h is not a free parameter

tree-level: $m_h \leq M_Z$

radiative corrections:

$$m_h^2 \rightarrow m_h^2 + \Delta m_h^2$$

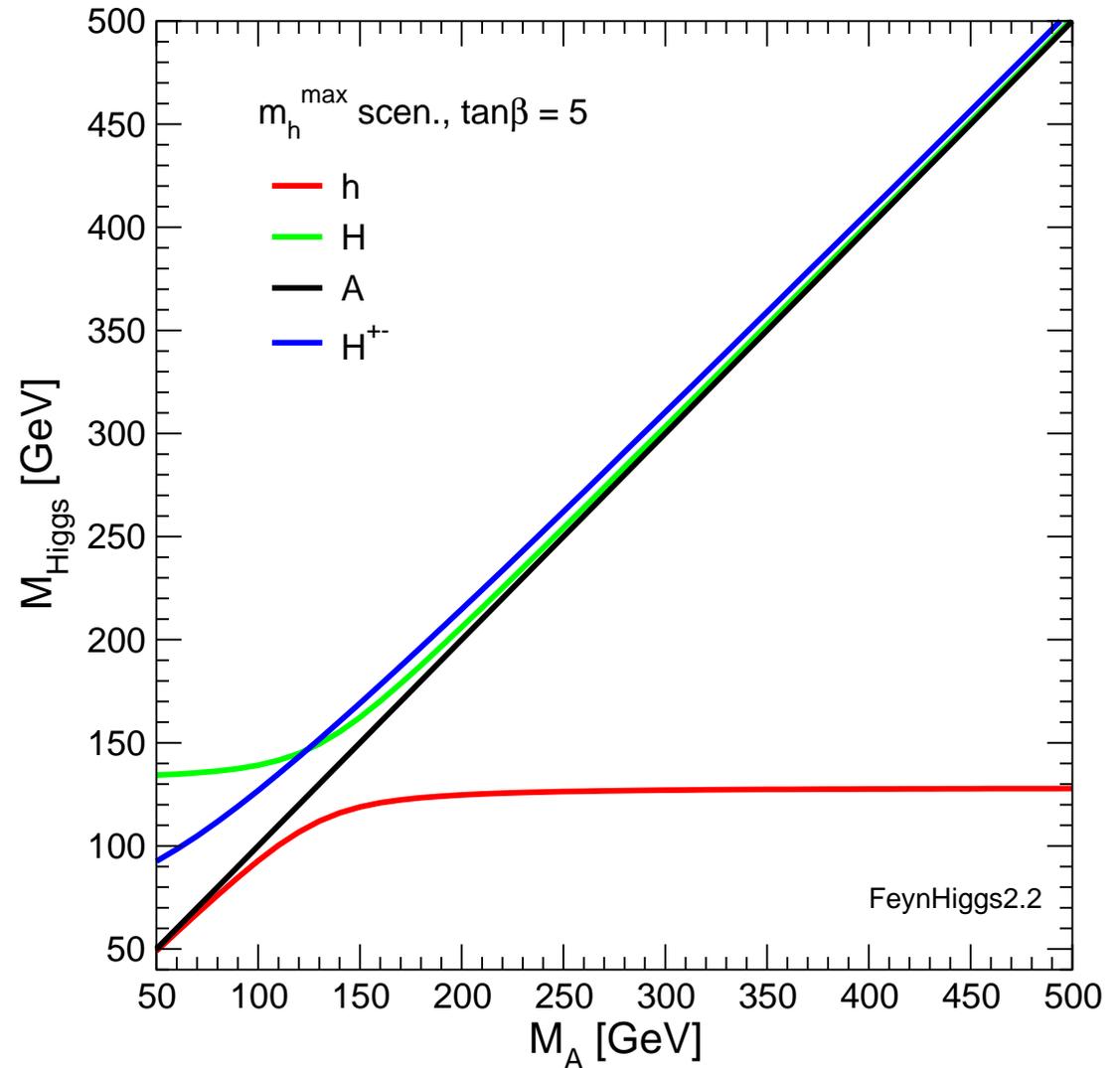
The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs is SM-like

The heavy MSSM Higgses:

$$M_A \approx M_H \approx M_{H^\pm}$$



3. Top physics (and electroweak precision observables) at the ILC

The top is guaranteed at the ILC \Rightarrow sure physics case

Top-quark mass is a fundamental parameter of the electroweak theory

By far the largest quark mass,
largest mass of all known fundamental particles

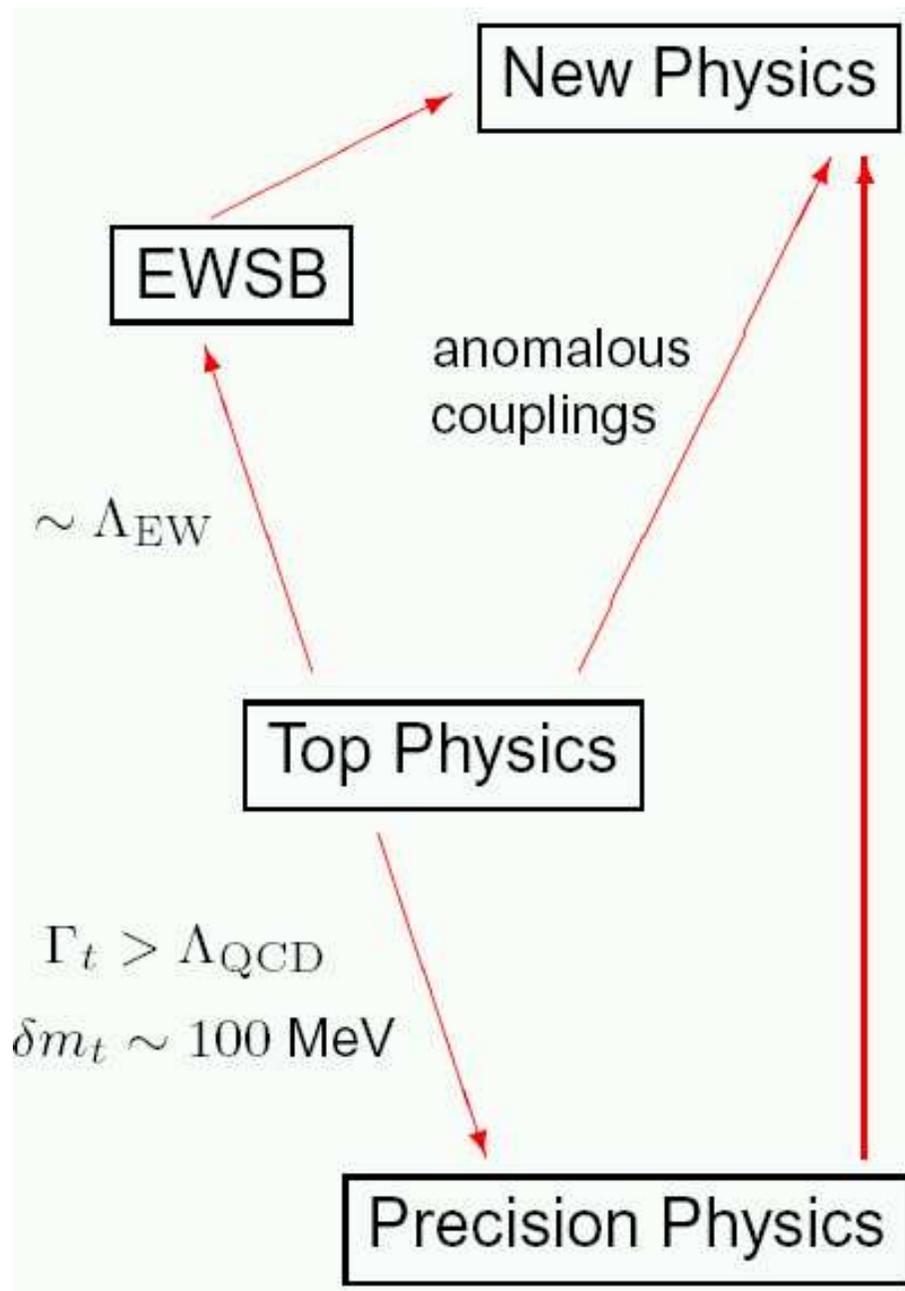
Window to new physics?

Large coupling to the Higgs boson; physics of flavor;
prediction of m_t from underlying theory?

Radiative corrections

\Rightarrow non-decoupling effects proportional to powers of m_t

\Rightarrow Need to know m_t very precisely in order to have
sensitivity to effects of new physics



EWSB: just a heavy quark?
 special role for t in EWSB?
 strong constraint on any model

Precision physics:

δm_t^{exp} leading parametric uncertainty
 → could obscure new physics

SUSY: m_t crucial input parameter
 drives SSB/unification

Little Higgs: heavier top

Tevatron: “rough” measurements
 of mass, couplings, BRs

LHC: the same (but better!?)

ILC: high precision of everything

What is the top mass?

Particle masses are **not** observables
one can only measure cross sections, decay rates, ...

Additional problem for the top mass:

what is the mass of a colored object?

Top pole mass is not IR safe (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\text{QCD}})$

Measurement of m_t :

- At **Tevatron, LHC**:
kinematic reconstruction, fit to invariant mass distribution
 \Rightarrow **“pole” mass**
- At the **ILC**:
mainly from threshold behavior \Rightarrow **threshold mass**

Experimental accuracy of m_t :

Measurement \Leftrightarrow comparison data from Monte Carlo

→ you measure the mass that is implemented in your MC

⇒ measured mass is not strictly model independent

⇒ 'Threshold mass' at the ILC: accuracy $\lesssim 20$ MeV

[*M. Martinez, R. Miquel '03*]

Transition to $\overline{\text{MS}}$ mass: [*A. Hoang et al. '00*]

$$\delta m_t \lesssim 100 \text{ MeV} \quad (\text{LC})$$

Are the uncertainties from unknown higher orders (QCD, electroweak, mixed) under control?

Situation at the Tevatron/LHC:

$$\delta m_t = 1\text{--}2 \text{ GeV} \quad (\text{Tev/LHC})$$

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Why is the ILC precision of m_t important?

Interplay of ILC precision for m_t and electroweak precision data

Precision observables: M_W , $\sin^2 \theta_{\text{eff}}$, m_h , $(g-2)_\mu$, b physics, ...

Theoretical prediction for M_W in terms
of M_Z , α , G_μ , Δr :

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$

\Updownarrow
loop corrections

Theoretical prediction for the effective mixing angle:

$$\sin^2 \theta_{\text{eff}} = \frac{1}{4 |Q_f|} \left(1 - \text{Re} \frac{g_V^f}{g_A^f} \right)$$

Higher order contributions:

$$g_V^f \rightarrow g_V^f + \Delta g_V^f, \quad g_A^f \rightarrow g_A^f + \Delta g_A^f$$

Leading m_t contributions:

One-loop result for M_W in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\begin{aligned} \Delta r_{1\text{-loop}} = & \Delta\alpha & - & \frac{c_W^2}{s_W^2} \Delta\rho & + & \Delta r_{\text{rem}}(M_H) \\ & \sim \log \frac{M_Z}{m_f} & & \sim m_t^2 & & \\ & \sim 6\% & & \sim 3.3\% & & \sim 1\% \end{aligned}$$

Leading m_t contribution to $\sin^2 \theta_{\text{eff}}$:

$$\Delta \sin^2 \theta_{\text{eff}} \approx - \frac{c_W^2 s_W^2}{c_W^2 - s_W^2} \Delta\rho \sim m_t^2$$

Experimental errors of the precision observables:

	today	Tev./LHC	ILC	GigaZ
$\delta \sin^2 \theta_{\text{eff}} (\times 10^5)$	17	17	–	1.3
δM_W [MeV]	34	15	10	7

Relevant SM parametric errors: $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2 \theta_{\text{eff}} [10^{-5}]$	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

To keep the **parametric error induced by m_t** at/below the level of other uncertainties:

$\Rightarrow \delta m_t \lesssim 0.2$ GeV for M_W

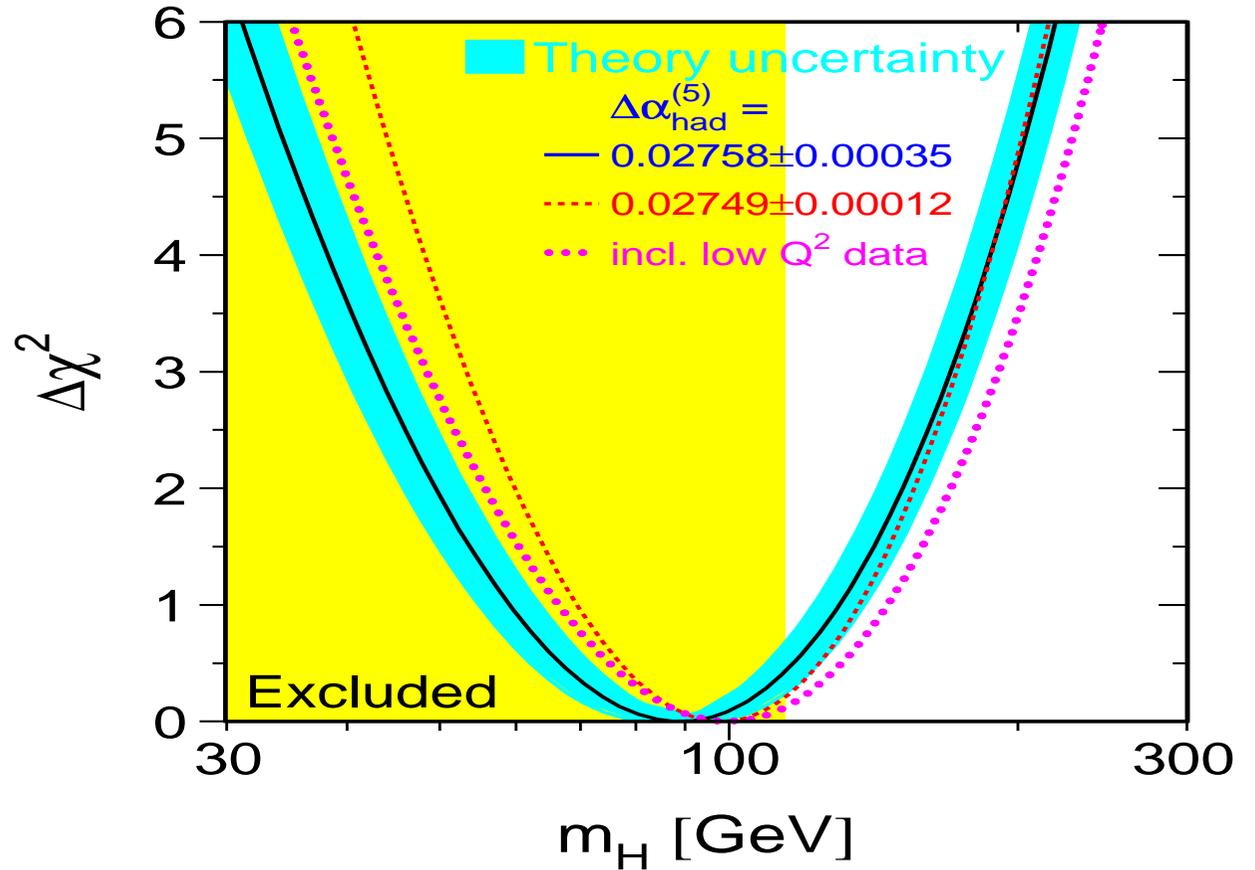
$\Rightarrow \delta m_t \lesssim 0.5$ GeV for $\sin^2 \theta_{\text{eff}}$

Example I: effect of improvement in m_t and EWPO data:

Current m_t value:
 $m_t = 172.5 \pm 2.3$ GeV

[Tevatron EWWG '06]

$M_W = 80.404 \pm 0.030$ GeV
 $\sin^2 \theta_{\text{eff}} = 0.23153 \pm 0.00016$



[LEPEWWG '06]

⇒ current best fit value: $M_H = 89_{-30}^{+42}$ GeV, $M_H < 175$ GeV at 95% C.L.

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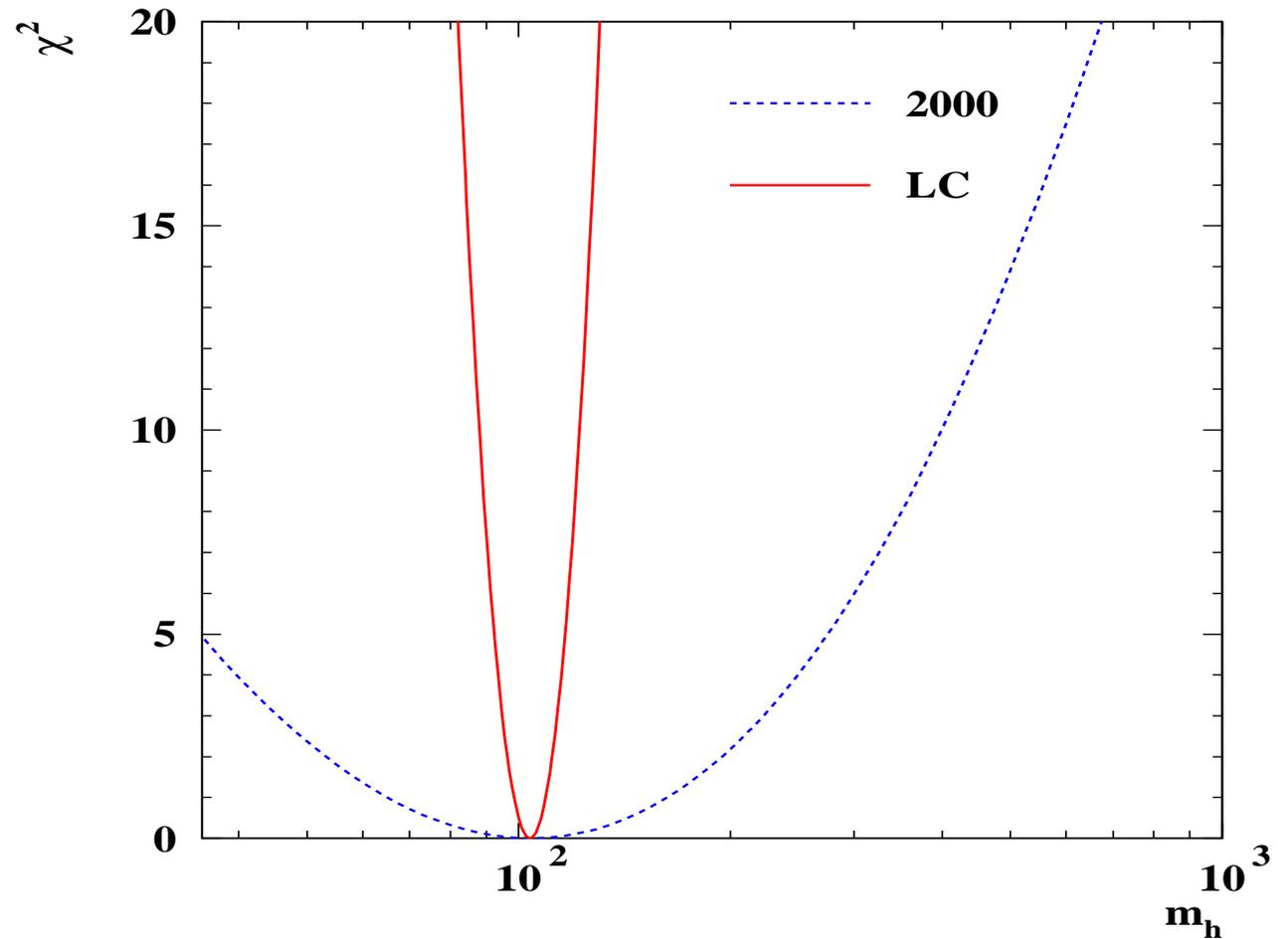
Future ILC m_t precision:

$$\delta m_t = \pm 0.1 \text{ GeV}$$

$$\delta M_W = 7 \text{ MeV}$$

$$\delta \sin^2 \theta_{\text{eff}} = 0.000013$$

[K. Mönig (Tesla TDR) '01]



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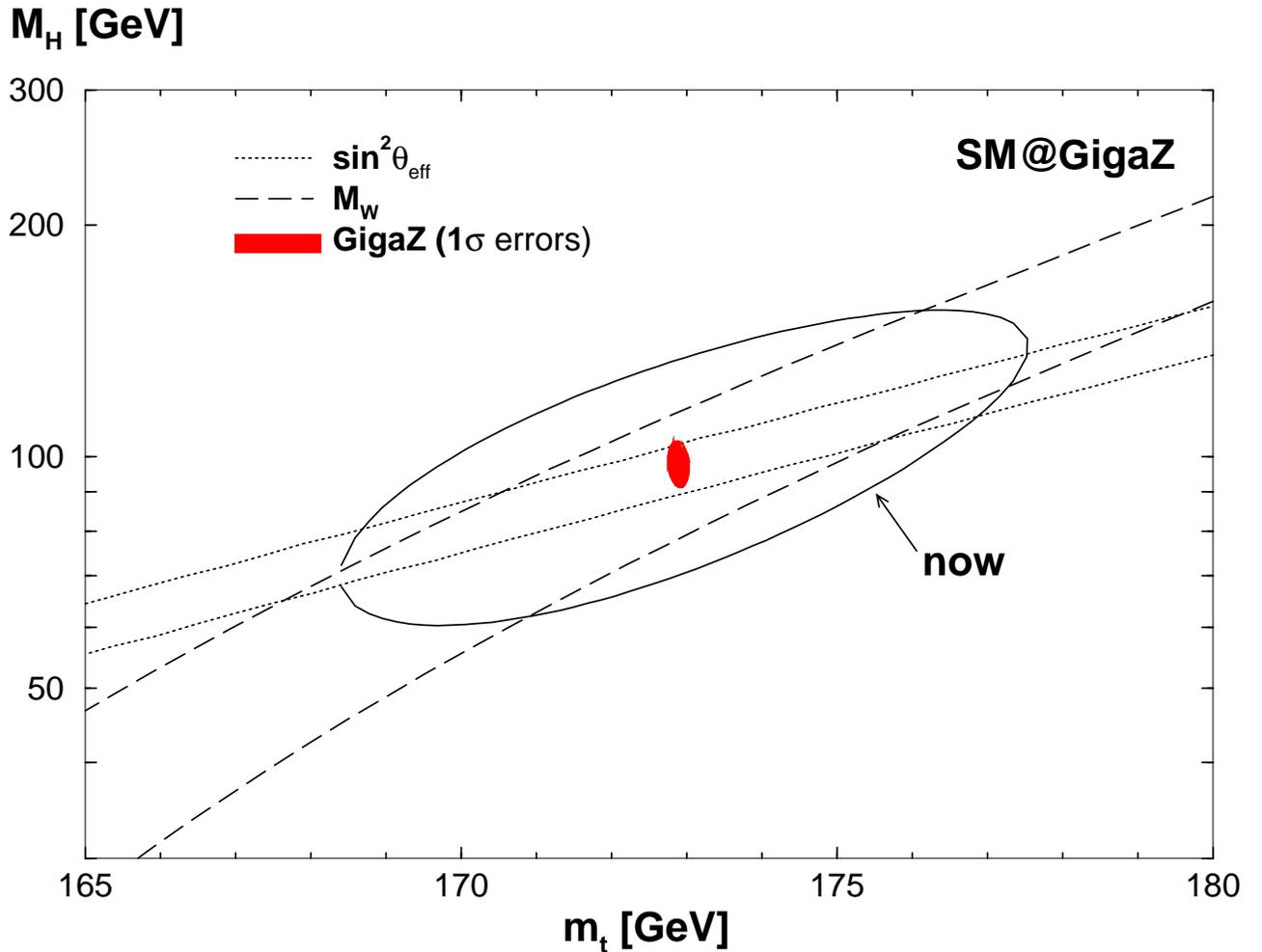
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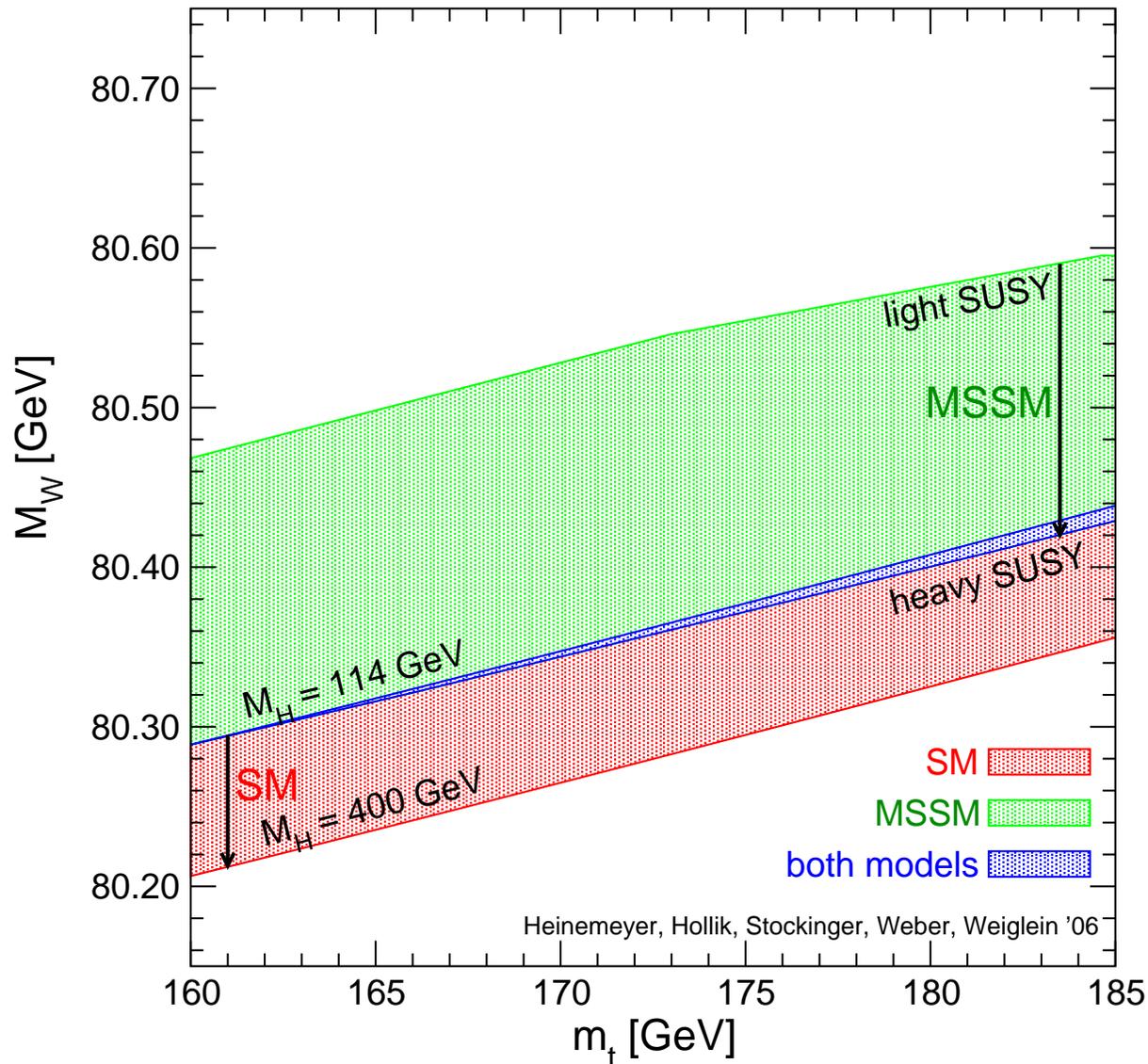
[J. Erler, S.H., W. Hollik,
G. Weiglein, P. Zerwas '00]



Example II: general scan:

Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '06]



MSSM band:
scan over
SUSY masses

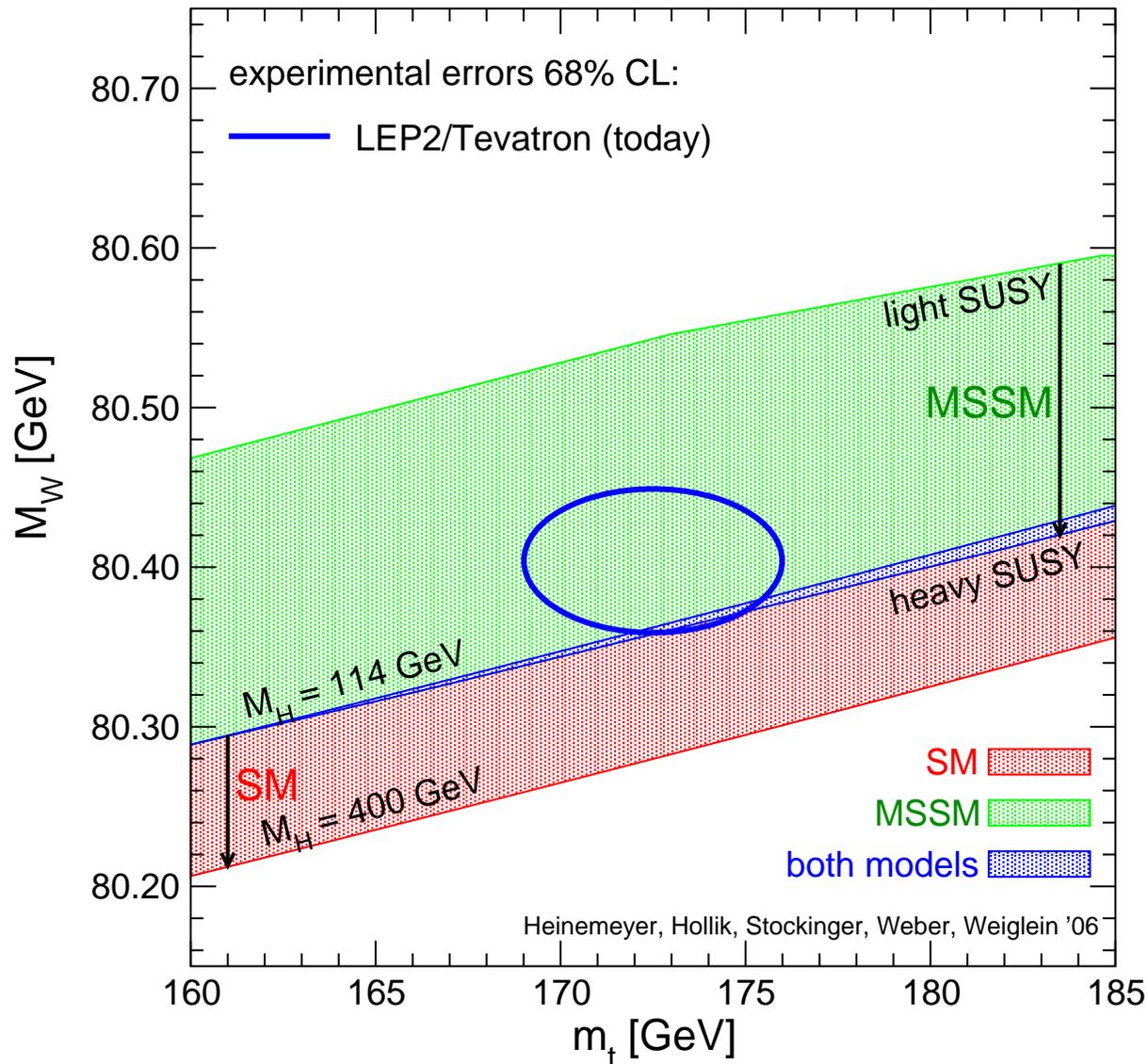
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SM is MSSM-like
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variation of M_H^{SM}

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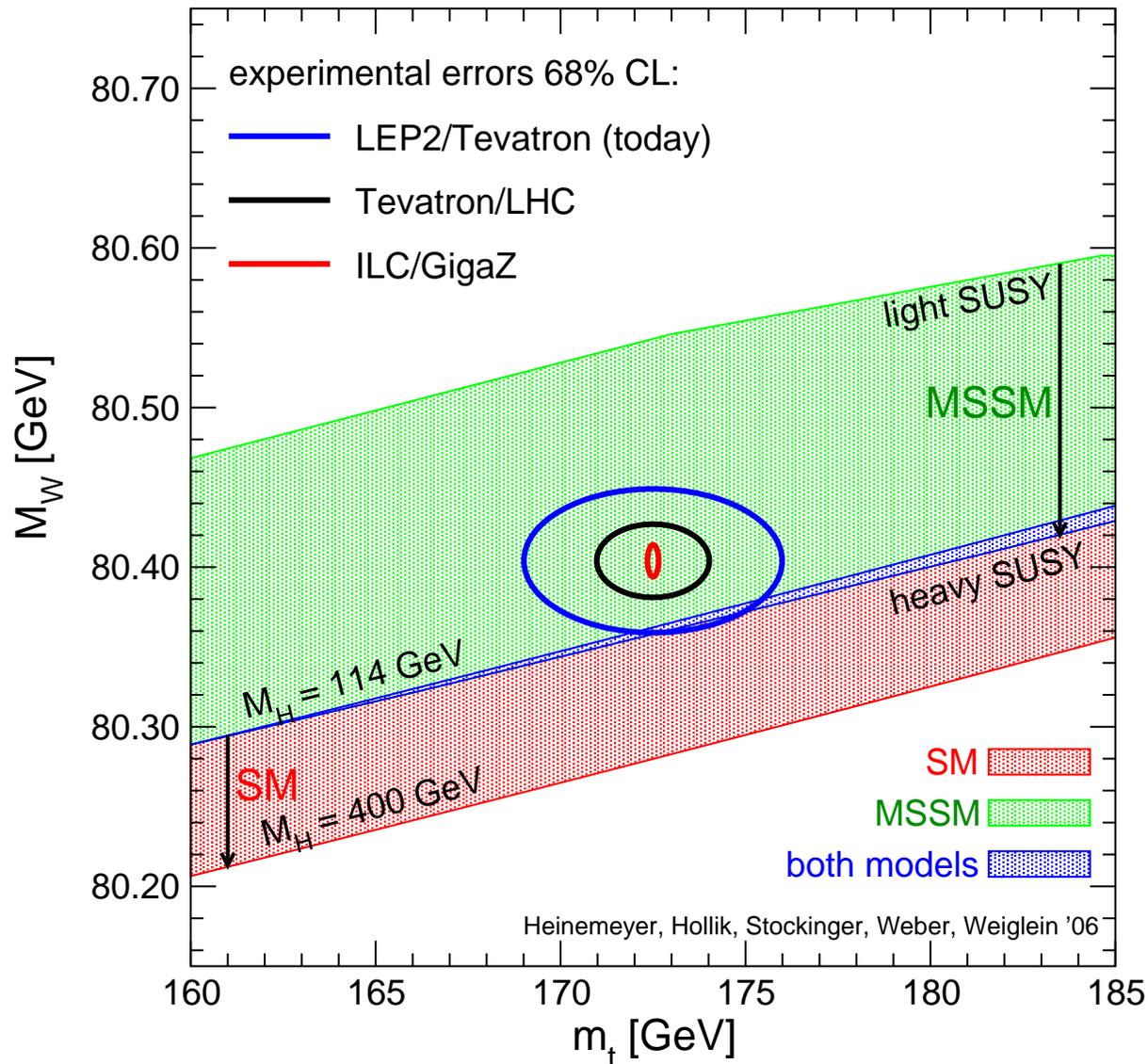
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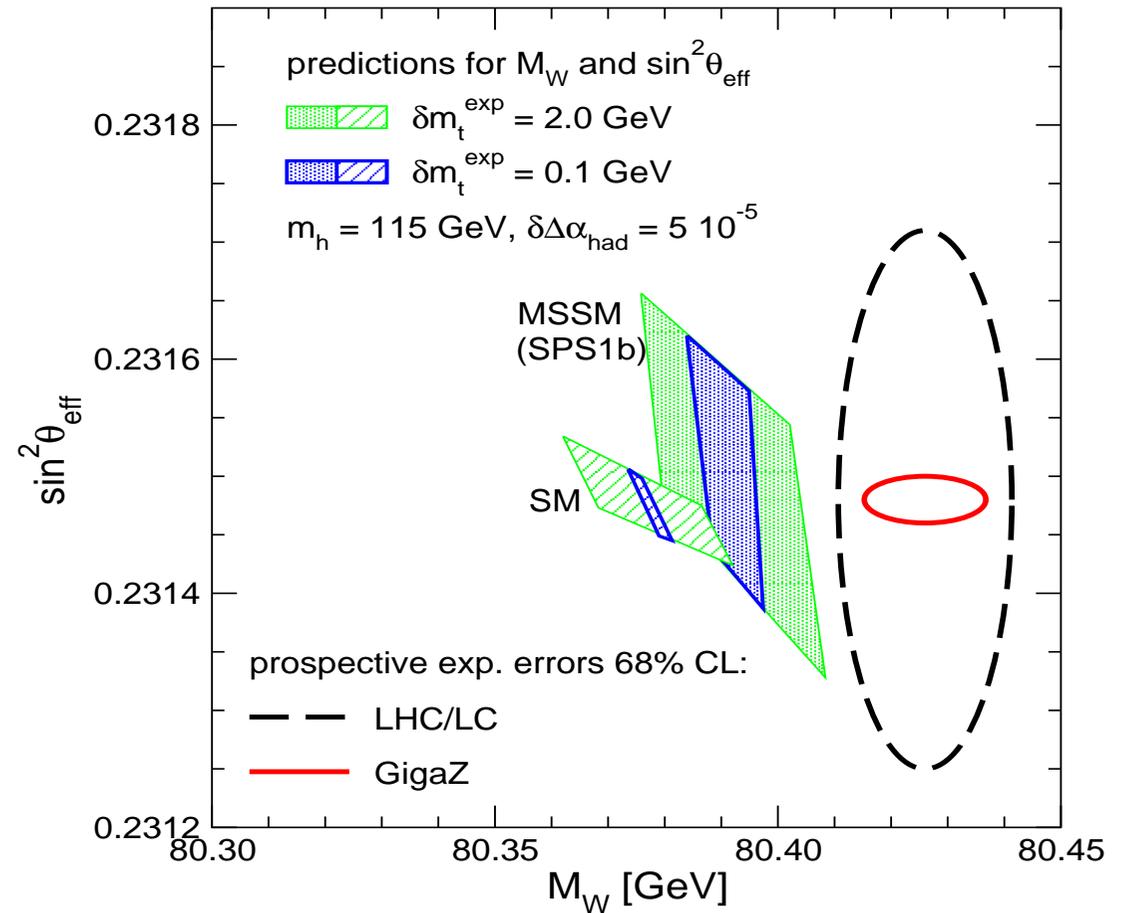
Example III: possible future scenario:

[S.H., S. Kraml, W. Porod, G. Weiglein '03]

SM: $M_H = 115$ GeV

MSSM: SPS 1b

all SUSY parameters varied
within realistic errors



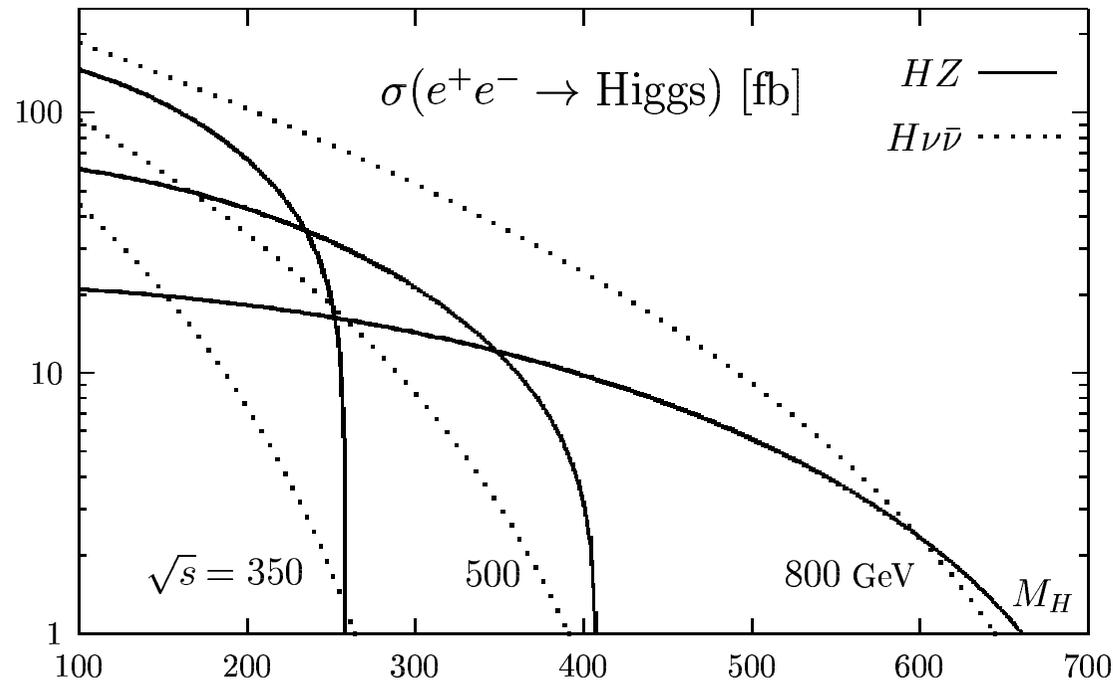
$\delta m_t = 0.1$ GeV vs. $\delta m_t = 2$ GeV

\Rightarrow SM: improvement by a factor ~ 10

\Rightarrow MSSM: improvement by a factor $\sim 2 - 3$

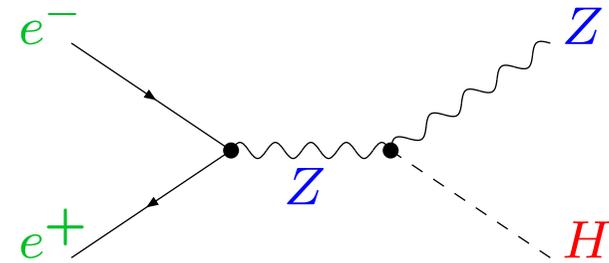
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Higgs production at the ILC:



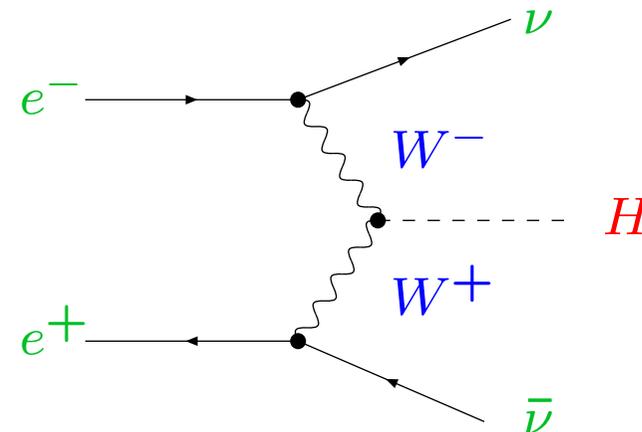
Higgs-strahlung:

$$e^+e^- \rightarrow Z^* \rightarrow ZH$$



weak boson fusion (WBF):

$$e^+e^- \rightarrow \nu\bar{\nu}H$$



⇒ Measurement of masses, couplings, ... in per cent/per mille

Some ILC specifics:

recoil method: $e^+e^- \rightarrow ZH, Z \rightarrow e^+e^-, \mu^+\mu^-$

⇒ total measurement of Higgs production cross section

⇒ **NO** additional theoretical assumptions needed for absolute determination of partial widths

⇒ all observable channels can be measured with high accuracy

Some ILC results ($500 \text{ fb}^{-1} @ \sqrt{s} = 350 \text{ GeV}$):

$$\delta M_H \approx 50 \text{ MeV}$$

$$\delta g_{ZZH} \approx 2.5\%, \quad \delta g_{WWH} \approx 2 - 5\%$$

$$\delta g_{Hb\bar{b}} \approx 1 - 2\% \text{ (for } M_H \lesssim 150 \text{ GeV)}$$

Some ILC specifics:

recoil method: $e^+e^- \rightarrow ZH, Z \rightarrow e^+e^-, \mu^+\mu^-$

⇒ total measurement of Higgs production cross section

⇒ **NO** additional theoretical assumptions needed for absolute determination of partial widths

⇒ all observable channels can be measured with high accuracy

Some ILC results ($500 \text{ fb}^{-1} @ \sqrt{s} = 350 \text{ GeV}$):

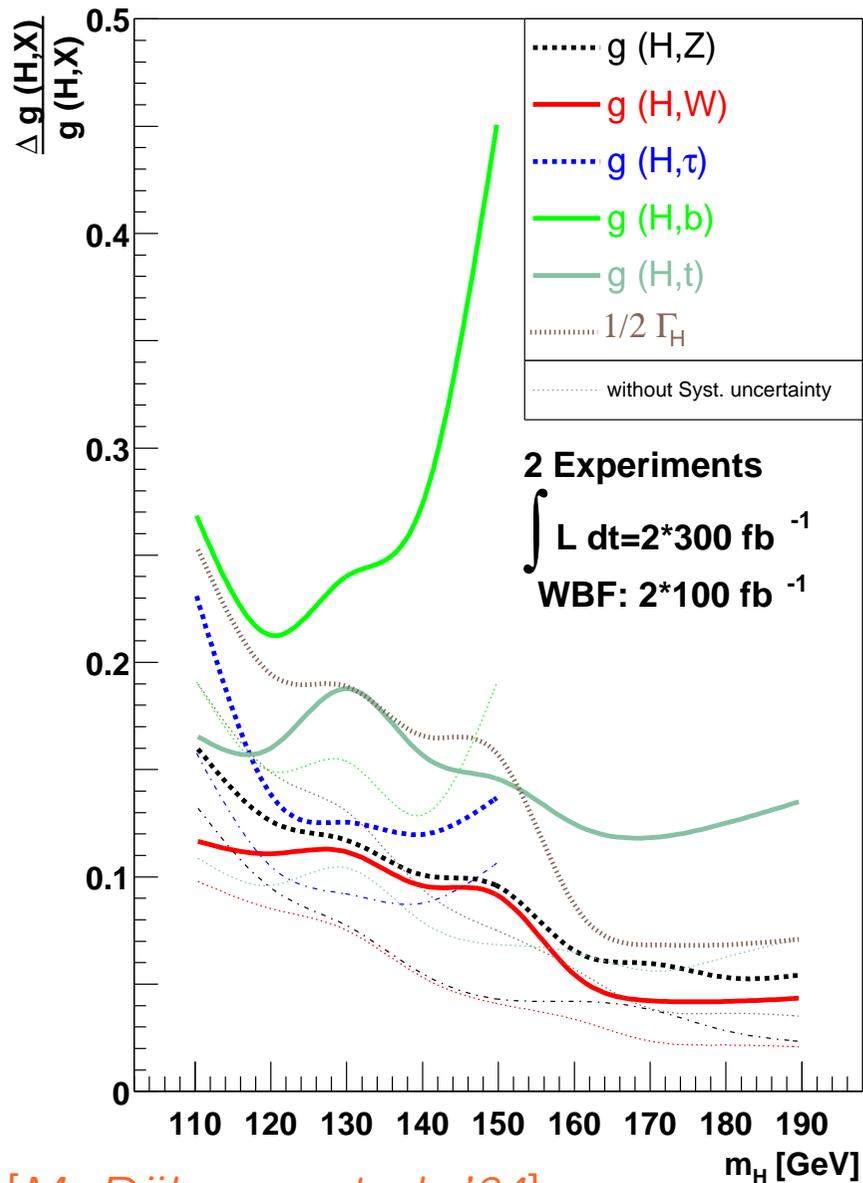
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How does this compare to the LHC?

The LHC will find a Higgs and measure its characteristics:



[M. Dürrssen et al. '04]

- mass: $\delta M_h \approx 200 \text{ MeV}$
- couplings: $(2 * 300 + 2 * 100) \text{ fb}^{-1}$:
 typical accuracies of 20-30%
 for $m_H \leq 150 \text{ GeV}$
 10% accuracies for HVV couplings
 above WW threshold

Assumption:

- $g_{HVV}^2 \leq g_{HVV,SM}^2 \times 1.05$
- SM rates for the Higgs

Problems:

- valid in weakly interacting models
- rates much lower than in SM ??
- physics can/will hide in 5% margin
- self-couplings out of reach

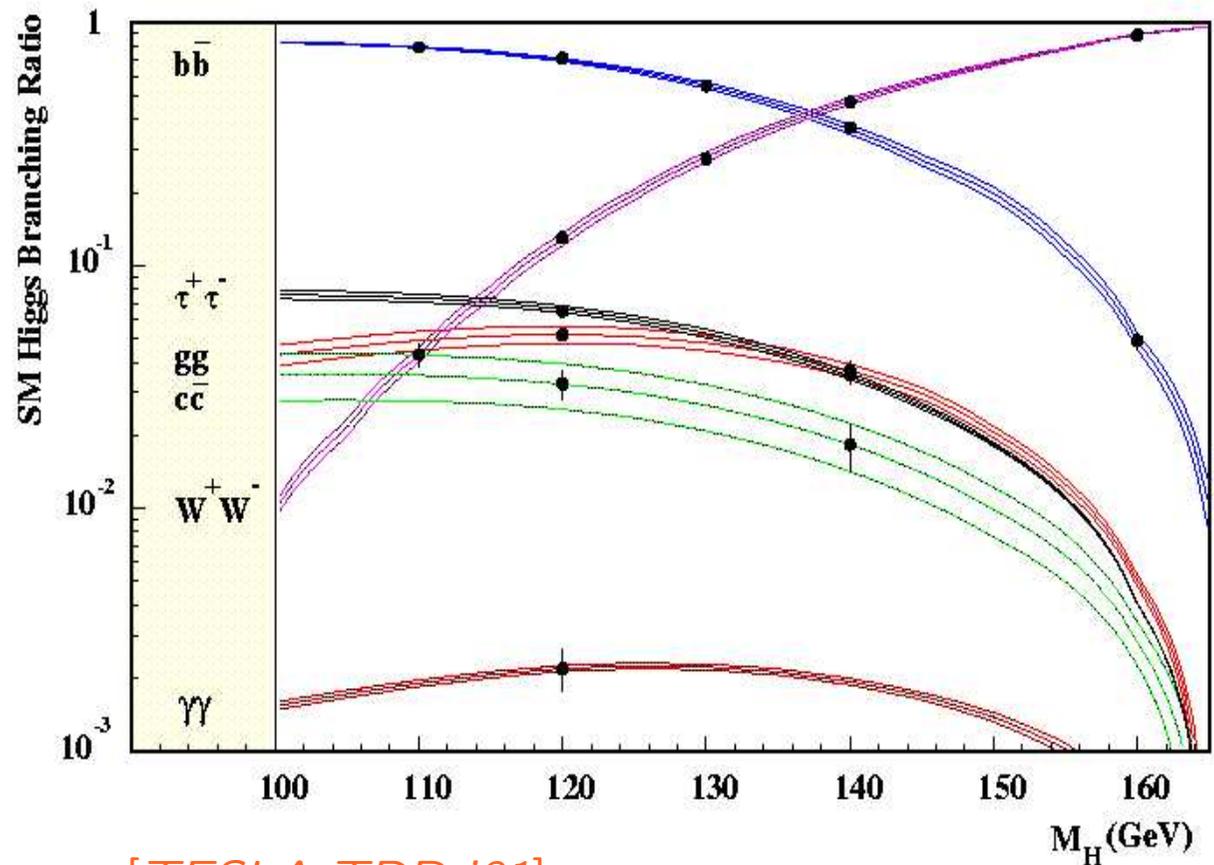
\Rightarrow ILC comes in

Compare to the ILC:

SM Higgs @ ILC:

Precise measurement of:

1. Higgs boson mass,
 $\delta M_H \approx 50 \text{ MeV}$
2. Higgs boson width
(direct/indirect)
3. Higgs boson couplings,
 $\mathcal{O}(\text{few}\%) \Rightarrow$
4. Higgs boson quantum
numbers: spin, \dots

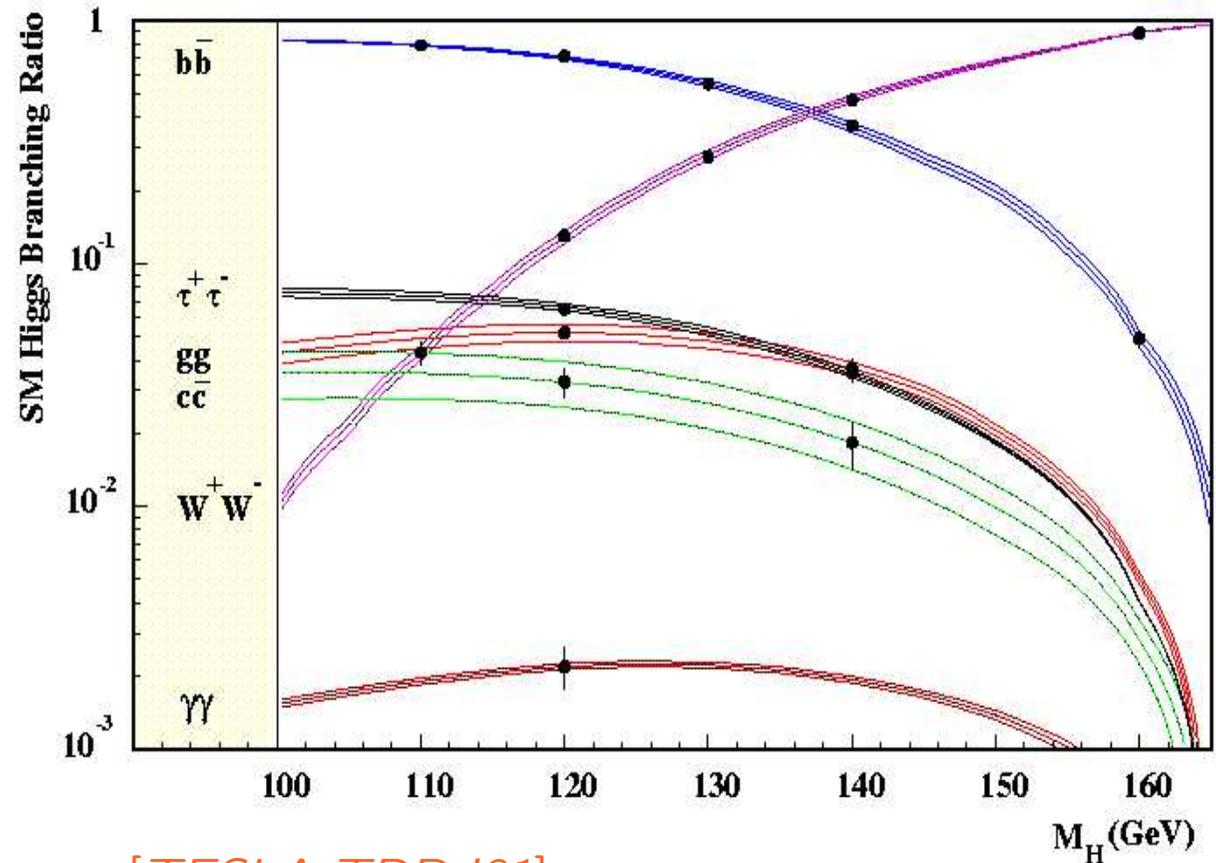


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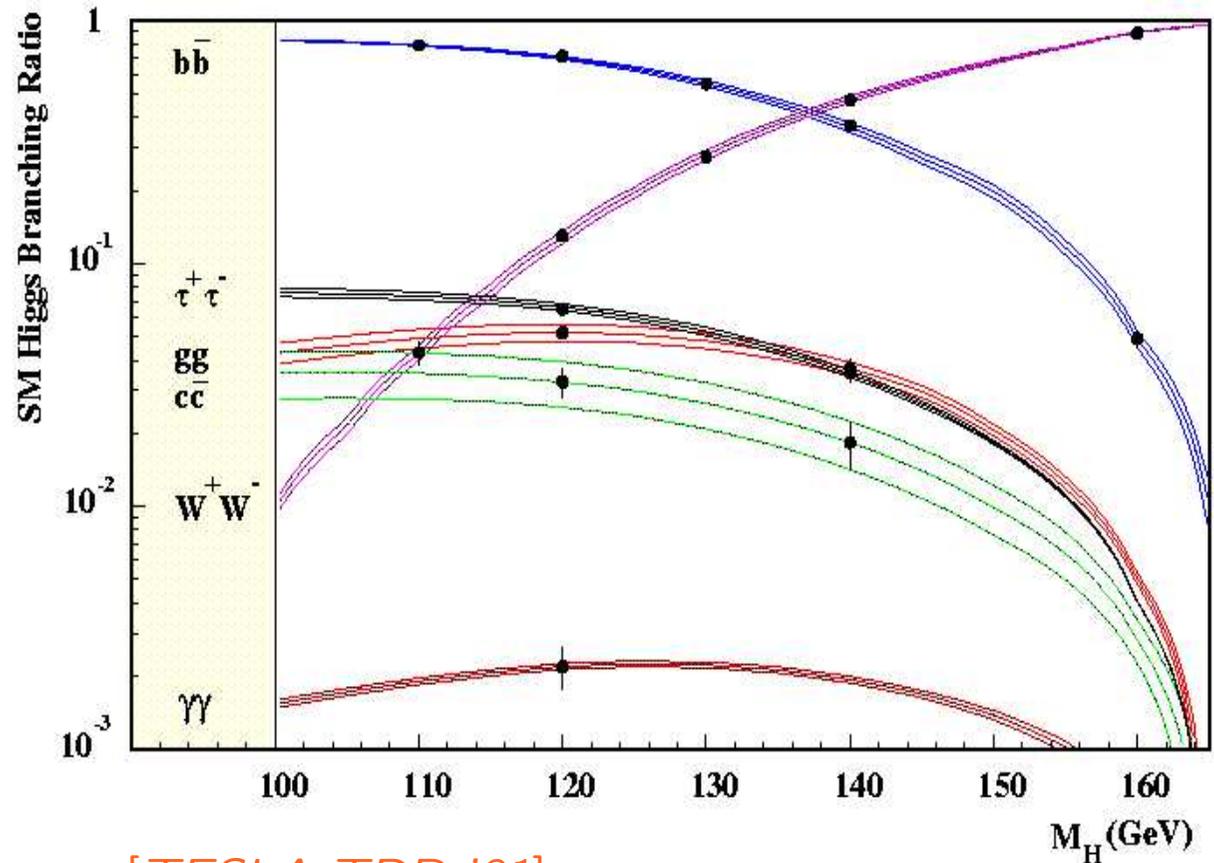
But do we need the ILC precision?

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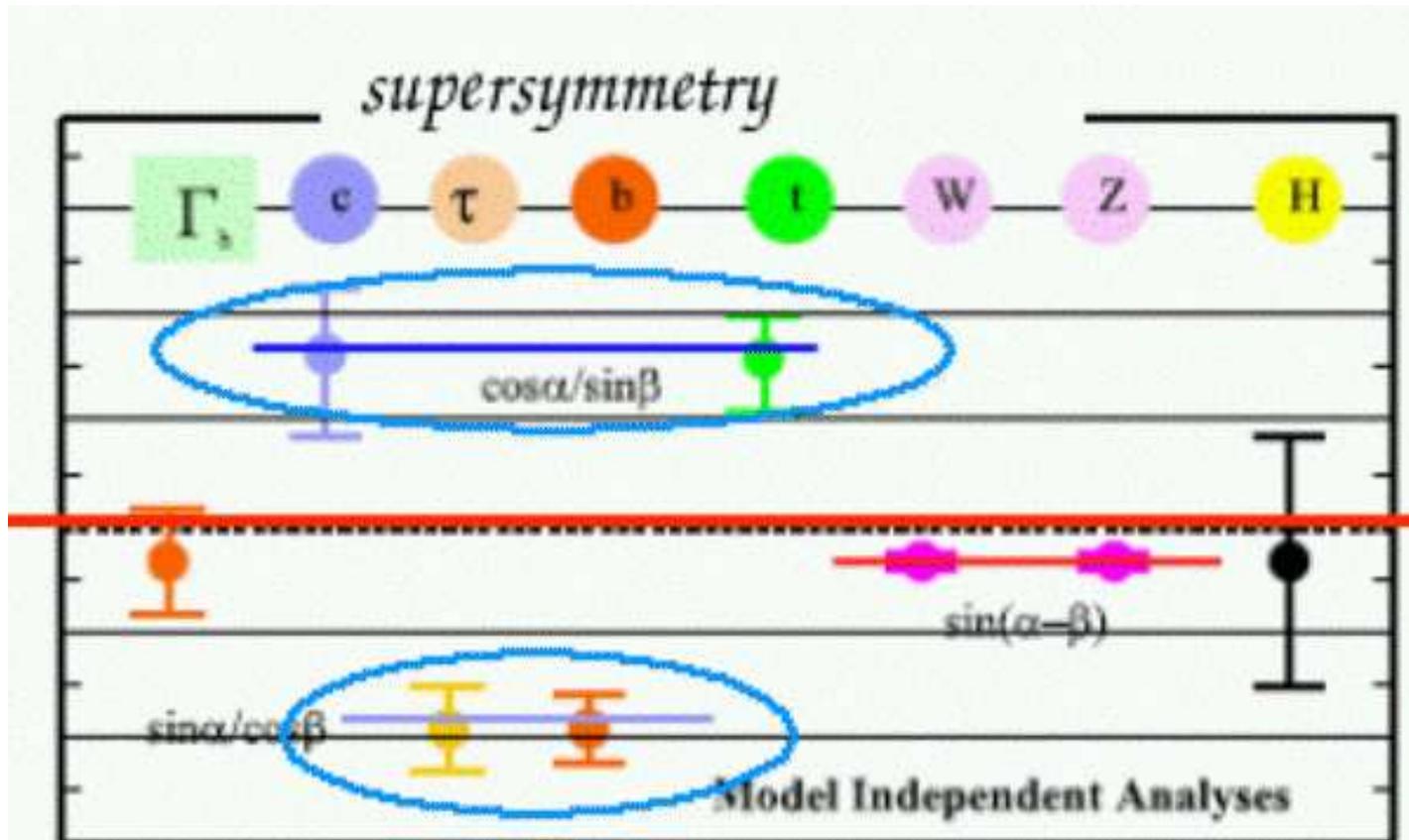


But do we need the ILC precision?

YES! To discriminate between the SM and extensions

Example I: Higgs couplings in the MSSM:

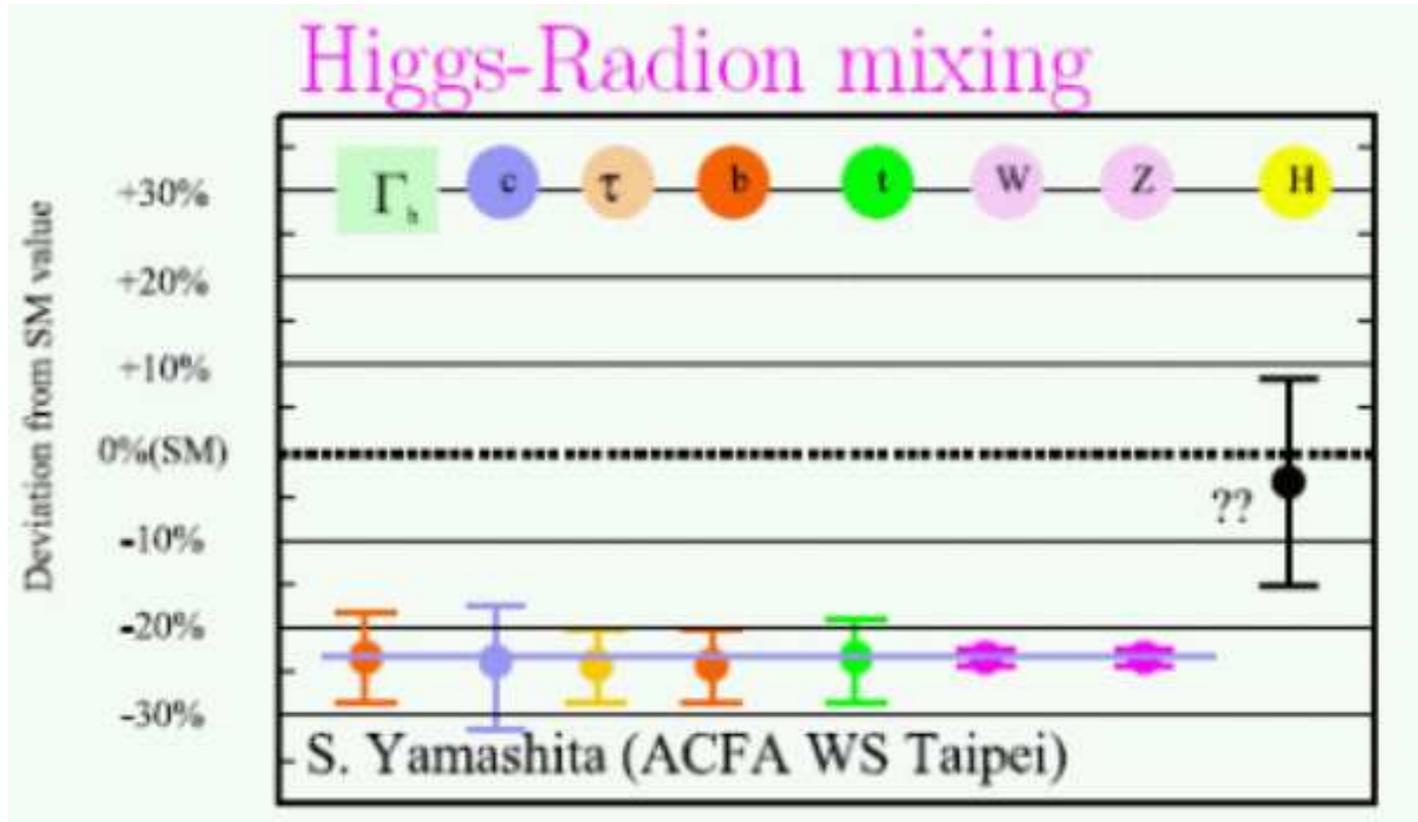
“Normal” MSSM scenario:



⇒ measurable deviations over large parts of the parameter space

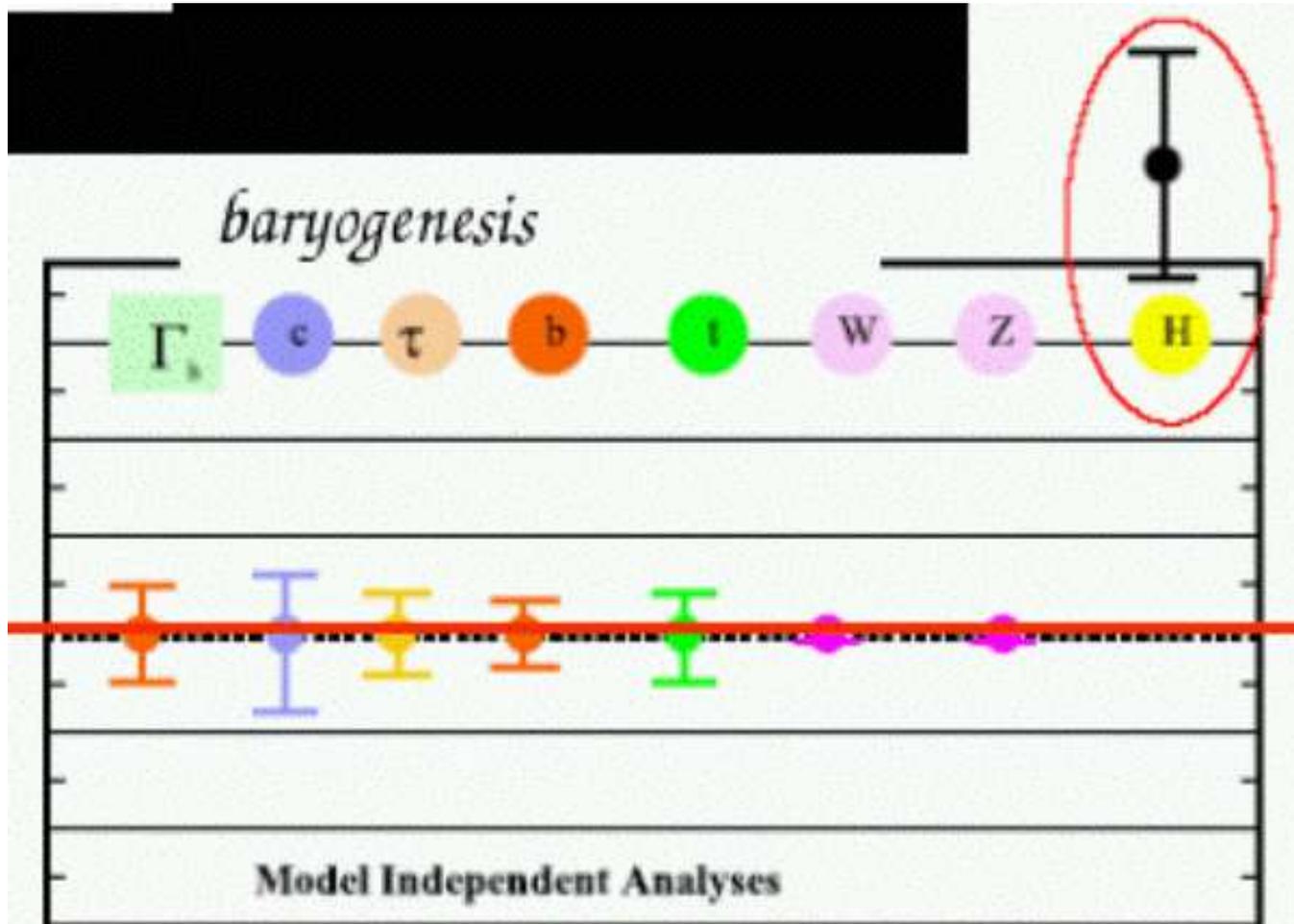
Example II: Higgs couplings in model with extra dimensions:

Effects of Kaluza Klein towers:



⇒ measurable deviations over large parts of the parameter space

Example III: Higgs couplings in a baryogenesis motivated SM extension:



⇒ Only Higgs self coupling deviates, measurement possible!

Tricky scenario:

The LHC finds only a **SM-like Higgs** and nothing else

Q: Do we still need the ILC?

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The LHC finds only a **SM-like Higgs** and nothing else

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A: Of course!

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Q: Do we still need the ILC?

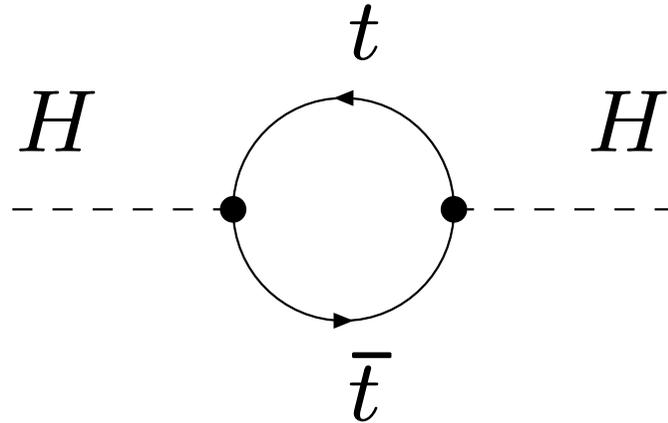
A: Of course! Or better: **even more!**

The ILC provides:

- precise **Higgs coupling** measurements
- precision observable measurements with the **GigaZ** option
- ⇒ Only the ILC can find deviations from the SM predictions via the various precision measurements
- ⇒ **Only the ILC can point towards extensions of the SM**

Going to extensions of the SM:

Nearly any model: large coupling of the Higgs to the top quark:



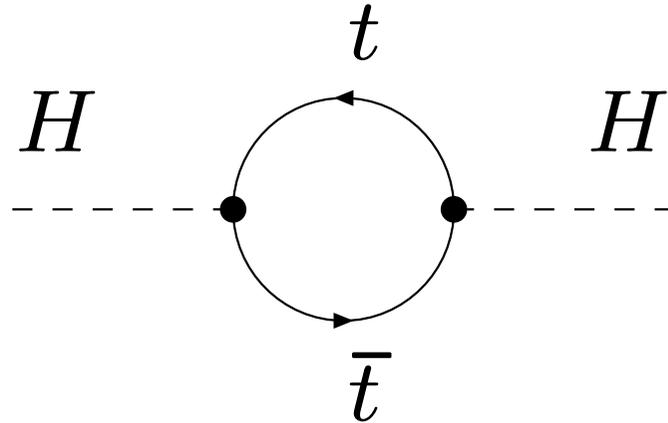
\Rightarrow one-loop corrections $\Delta m_h^2 \sim G_\mu m_t^4$

$\Rightarrow M_H$ depends sensitively on m_t in all models where M_H can be predicted (SM: M_H is free parameter)

SUSY as an example: $\Delta m_t \approx \pm 2 \text{ GeV} \Rightarrow \Delta m_h \approx \pm 2 \text{ GeV}$

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SUSY as an example: $\Delta m_t \approx \pm 2 \text{ GeV} \Rightarrow \Delta m_h \approx \pm 2 \text{ GeV}$

⇒ Precision Higgs physics needs precision top physics

Contrary to the SM:

m_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta m_h^2 \sim G_\mu m_t^4 \log \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of m_h , Higgs couplings \Rightarrow test of the theory

LHC: $\Delta m_h \approx 0.2$ GeV

ILC: $\Delta m_h \approx 0.05$ GeV

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ILC: $\Delta m_h \approx 0.05$ GeV

\Rightarrow LHC precision of m_h requires ILC precision of m_t

Upper bound on m_h in the MSSM:

“Unconstrained MSSM”:

M_A , $\tan \beta$, 5 parameters in \tilde{t} - \tilde{b} sector, μ , $m_{\tilde{g}}$, M_2

$$m_h \lesssim 135 \text{ GeV}$$

for $m_t = 172.5 \text{ GeV}$

(including theoretical uncertainties from unknown higher orders)

Obtained with:

FeynHiggs

[S.H., W. Hollik, G. Weiglein '98 – '02]

[T. Hahn, S.H., W. Hollik, G. Weiglein '03 – '06]

www.feynhiggs.de

→ all Higgs masses, couplings, BRs (easy to link, easy to use :-)

5. SUSY at the ILC

Production of SUSY particles at the LHC will in general result in complicated final states, e.g.

$$\tilde{g} \rightarrow \bar{q}\tilde{q} \rightarrow \bar{q}q\tilde{\chi}_2^0 \rightarrow \bar{q}q\tilde{\tau}\tau \rightarrow \bar{q}q\tau\tau\tilde{\chi}_1^0$$

Production of uncolored particles via cascade decays often dominates over direct production

Many states are produced at once

⇒ Main background for SUSY is SUSY itself!

Searches for MSSM Higgs bosons:

good prospects for detecting light Higgs h

H/A discovery possible in significant part of parameter space

In order to establish SUSY experimentally:

Need to demonstrate that:

- every particle has superpartner
- their spins differ by $1/2$
- their gauge quantum numbers are the same
- their couplings are identical
- mass relations hold

...

⇒ Precise measurements of masses, branching ratios, cross sections, angular distributions, ... mandatory for

- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

⇒ We need both: hadron colliders (Tev./LHC) and high luminosity ILC

Requires clean experimental environment, high luminosity, beam polarization, . . .

⇒ High luminosity ILC necessary, complementary to hadron machines

SUSY searches at the ILC:

Clean signatures, small backgrounds

Thresholds for pair production of SUSY particles

⇒ precise determination of mass and spin of SUSY particles, mixing angles, complex phases, . . .

Limited by kinematic reach

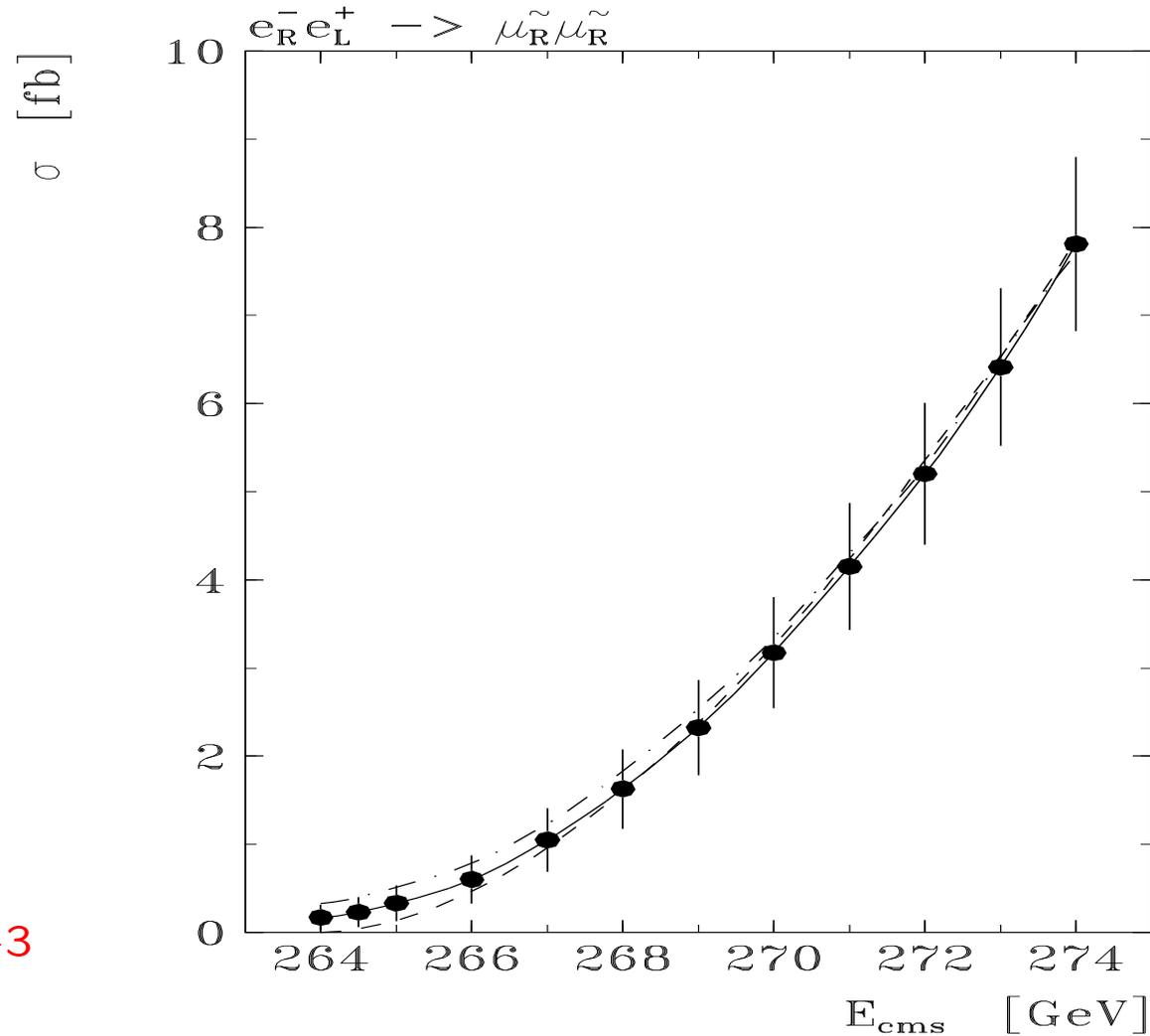
Good prospects for production of uncolored particles

⇒ LHC / ILC complementarity

Example for SUSY physics at the ILC (I):

Determination of mass and spin of $\tilde{\mu}_R$ from production at threshold:

[TESLA TDR '01]



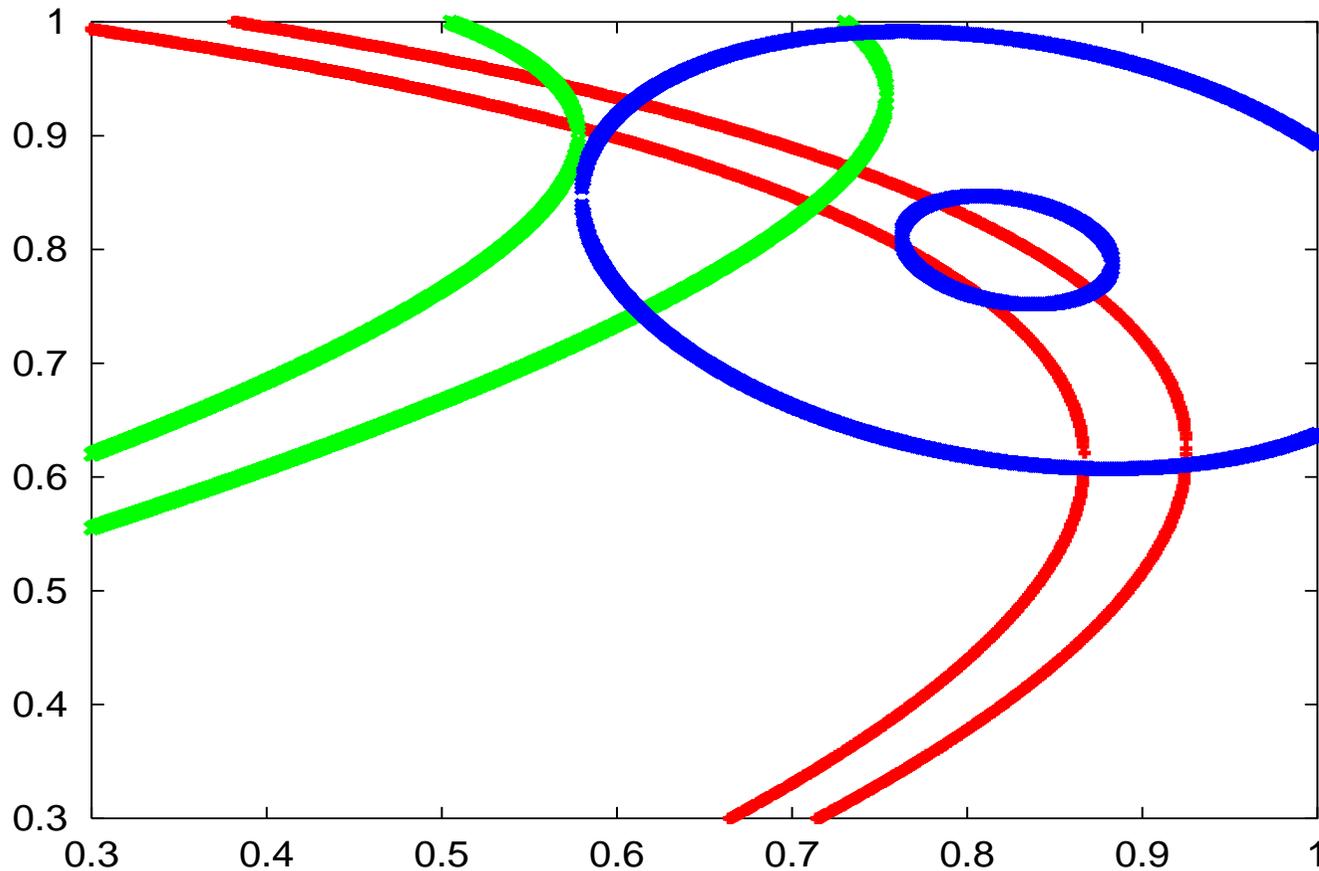
$$\Rightarrow \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

\Rightarrow test of $J = 0$ hypothesis

Example for SUSY physics at the ILC (II):

Determination of ϕ_R, ϕ_L in neutralino sector from measurement of $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $P_{e^-} = \pm 80\%, P_{e^+} = \pm 60\%$ $\mathcal{L} = 500 \text{ fb}^{-1}$:

[*K. Desch, J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '03*]



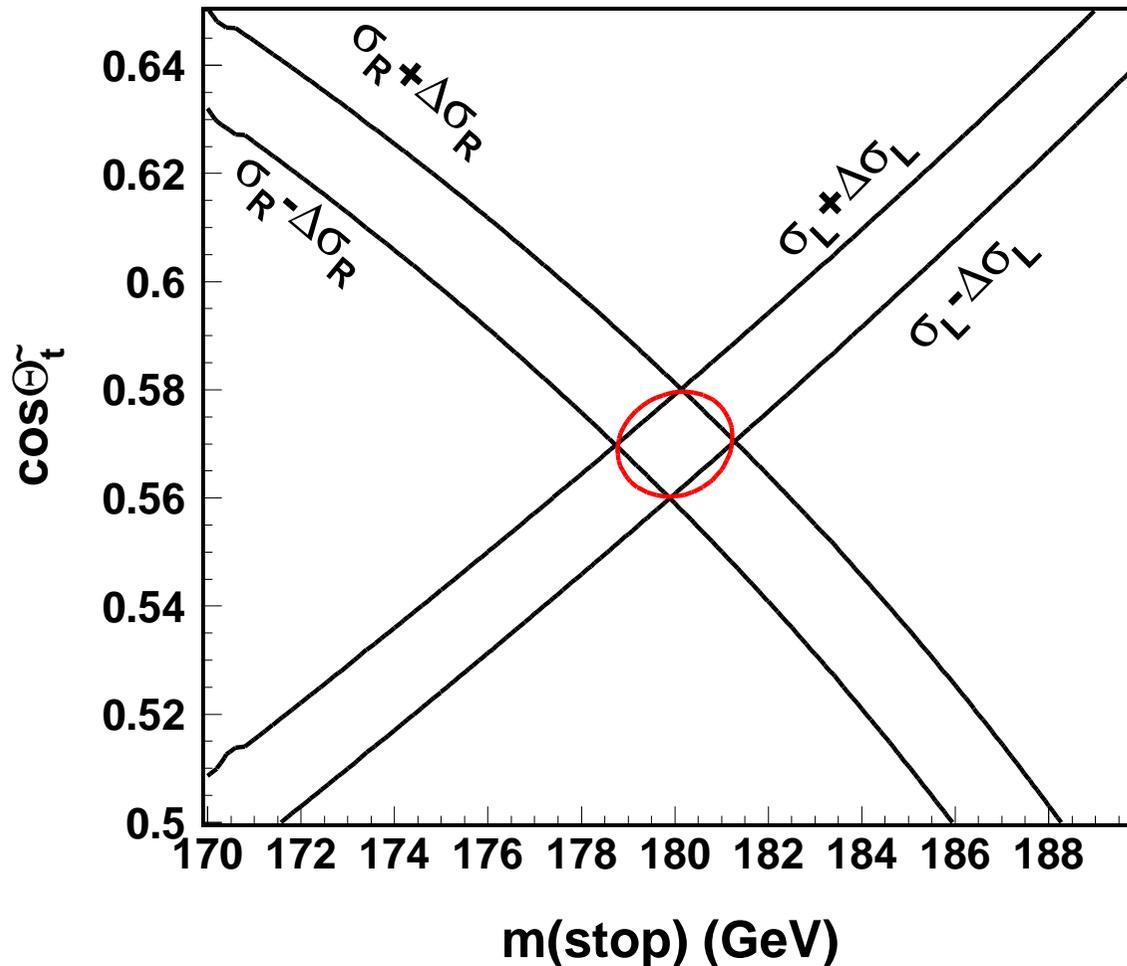
$\Rightarrow \cos 2\phi_L = [0.62, 0.72], \cos 2\phi_R = [0.87, 0.91]$

Example for SUSY physics at the ILC (III):

Determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$ from $\sigma(e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1)$ with polarized beams:

[R. Keränen, H. Nowak, A. Sopczak '00]

stop into c neutralino 80/60 pol



$$\Rightarrow \frac{\Delta m_{\tilde{t}_1}}{m_{\tilde{t}_1}} \approx 0.5\%,$$
$$\frac{\Delta \cos\theta_{\tilde{t}}}{\cos\theta_{\tilde{t}}} \approx 1.5\%$$

Complementarity of LHC and ILC:

⇒ Results obtained at one collider can be used for improving experimental analyses at the other

⇒ investigated in “LHC / ILC Study Group”

www.ippp.dur.ac.uk/~georg/lhclc

Collaborative effort of LHC and ILC community

Started in spring 2002, currently about 190 working group members from ATLAS, CMS, LC working groups, theory + Tevatron contact person

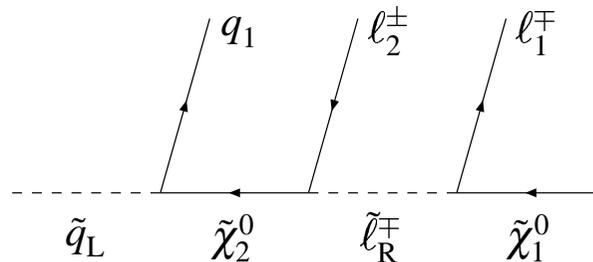
⇒ extensive document: hep-ph/0410364

Example (I): SUSY parameters at LHC and ILC

Reconstruction of sparticle masses at the LHC

[*B. Gjelsten, E. Lytken, D. Miller, P. Osland, G. Polesello, M. Chiorboli, A. Tricomi*]

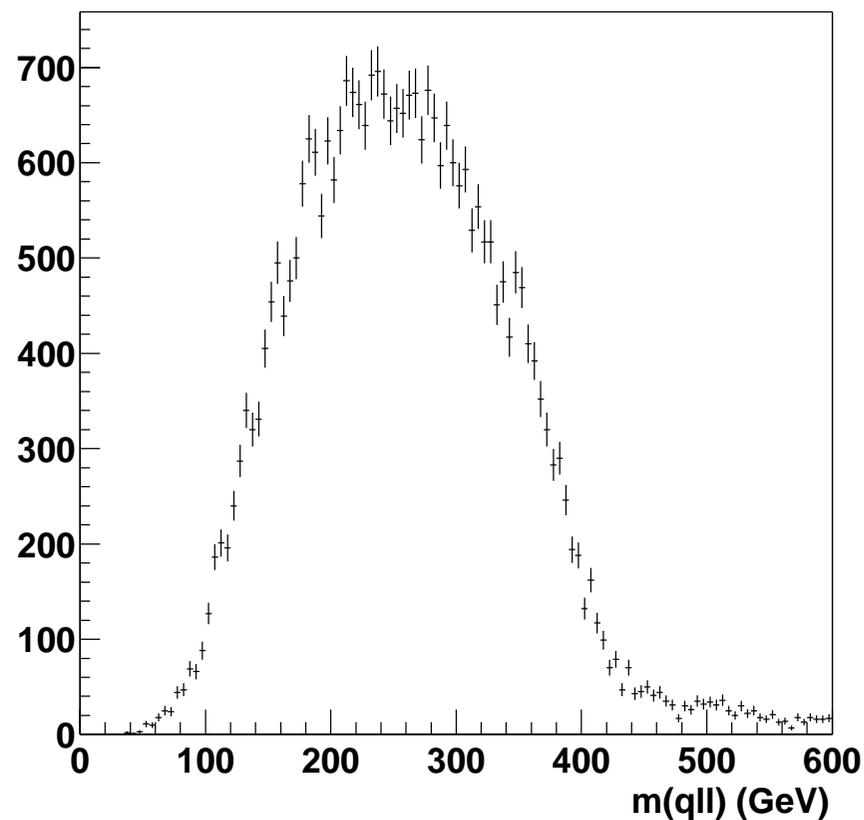
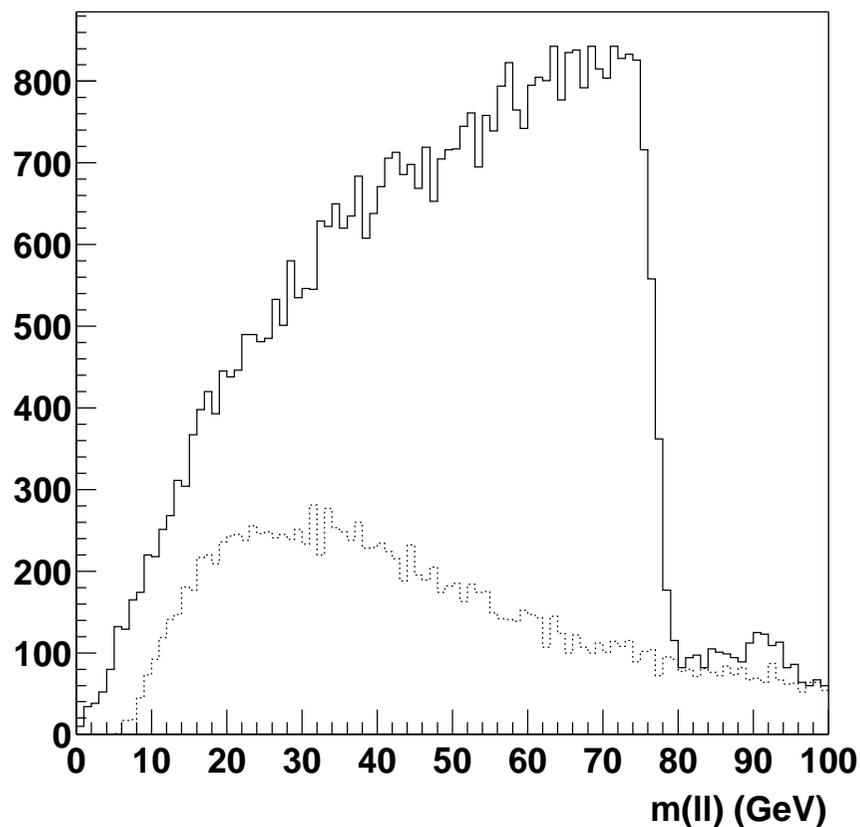
Complicated decay chains for squarks and gluinos



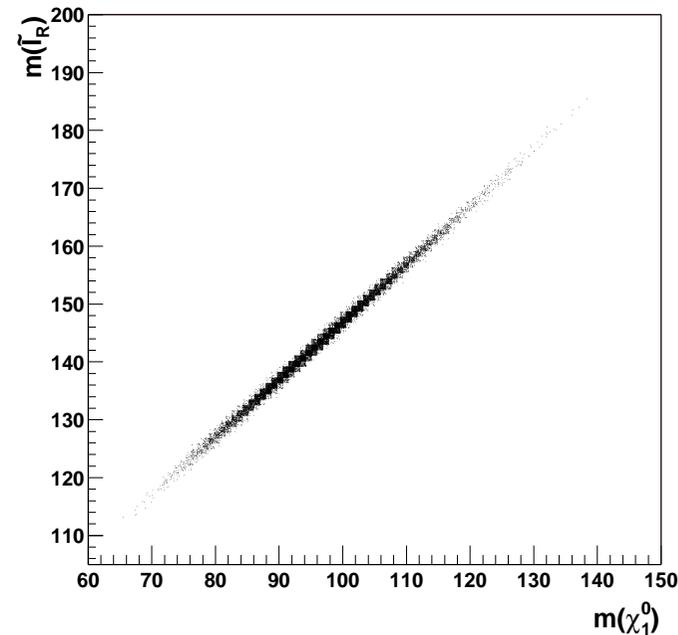
Examples worked out for SPS1a from ATLAS and CMS
main tool: dilepton “edge” from $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$

Sbottom/squark and gluino reconstruction:

Edge in same flavor-opposite sign lepton distribution (left), invariant mass distributions with kinematical endpoints (right)



Strong correlation between slepton mass and LSP mass, LSP mass can be constrained at LHC at the 10% level only:

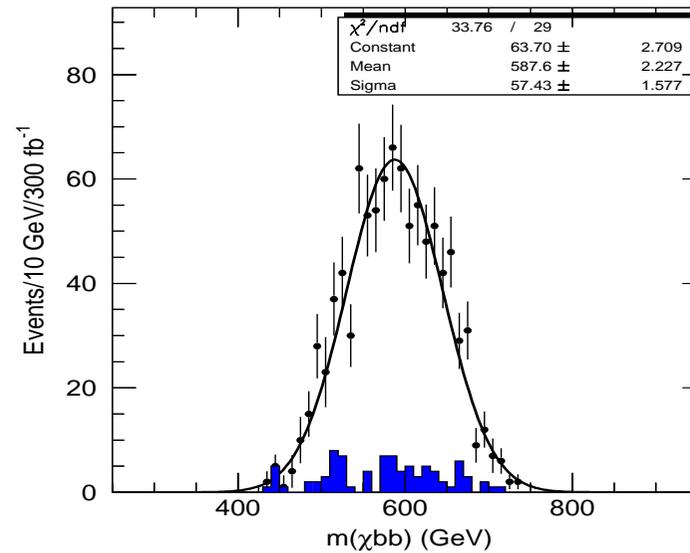
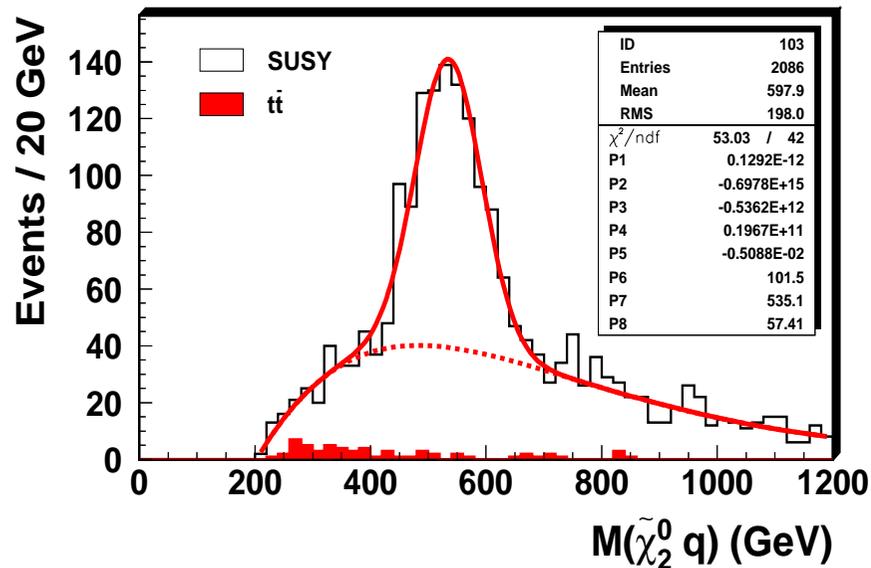


⇒ Take LSP mass as input from ILC

⇒ feed LSP mass from ILC in the LHC analysis

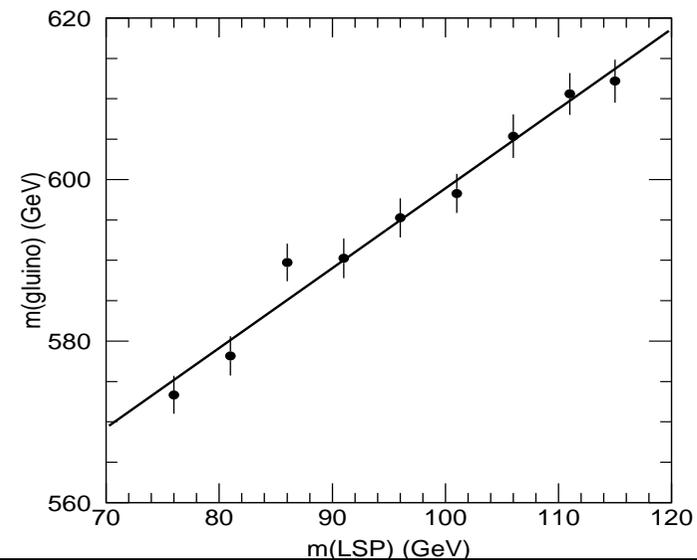
⇒ Get sbottom/squark mass if LSP mass is known

Squark peak (left) and gluino reconstruction from $(\chi_2^0 bb)$ invariant mass distribution (right):



$m_{\tilde{g}}$ as function of the LSP mass:

$$\Rightarrow \Delta m_{\tilde{g}} \approx \Delta m_{\text{LSP}}$$



Accuracies for the case of the LHC alone (left) and with the LC measurement of the LSP mass with $\delta m_{\text{LSP}} = \pm 0.05$ GeV:

[LHC/ILC Study Group report '04]

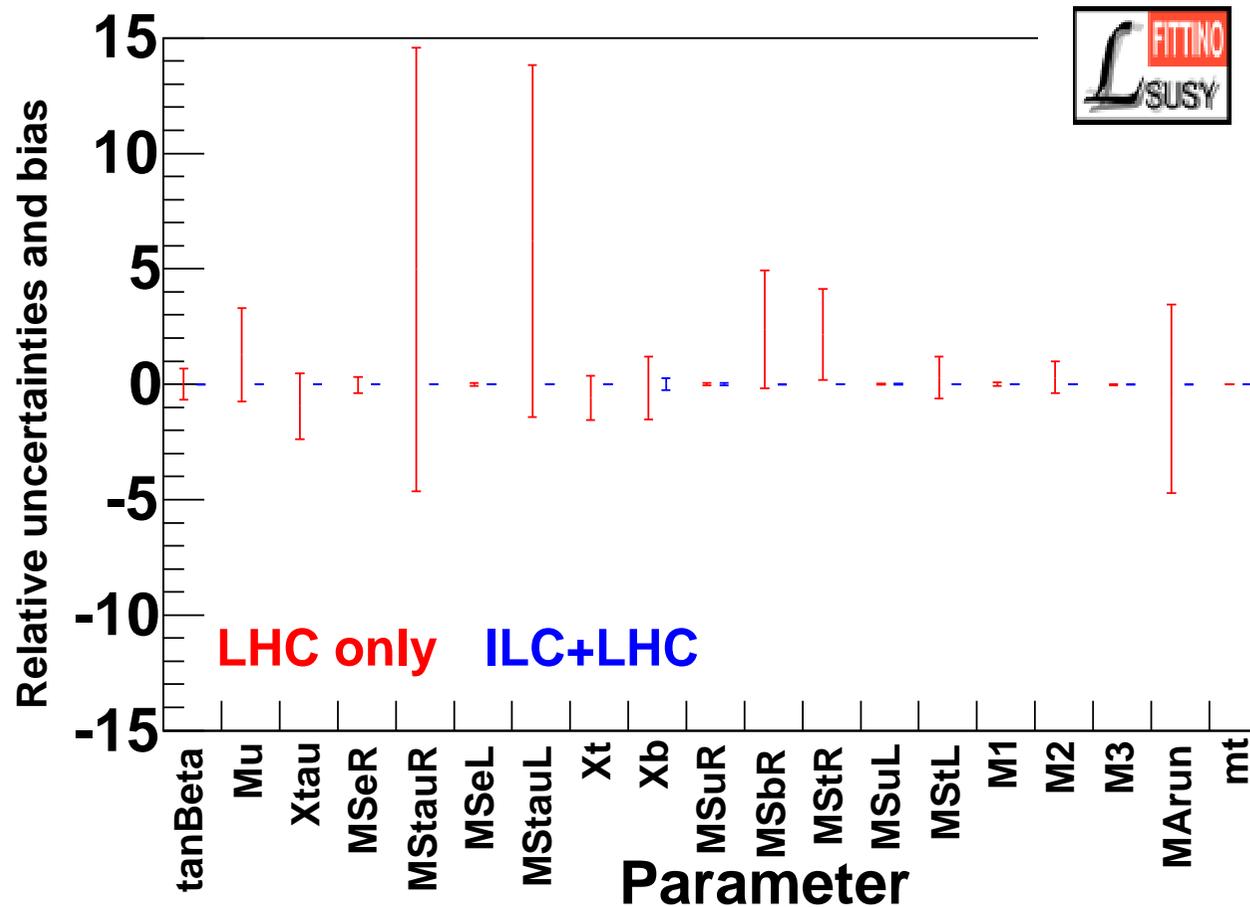
	LHC [GeV]	LHC + ILC [GeV]
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05
$\Delta m_{\tilde{\chi}_2^0}$	4.2	0.08
$\Delta m_{\tilde{t}_L}$	4.8	0.05
$\Delta m_{\tilde{b}_1}$	7.1	5.7
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\tilde{g}}$	8.0	6.5

⇒ ILC input improves accuracy significantly

Finally: global fit to all measurements

[P. Bechtle, K. Desch, P. Wienemann '05]

Compare **LHC** and **LHC \oplus ILC** :

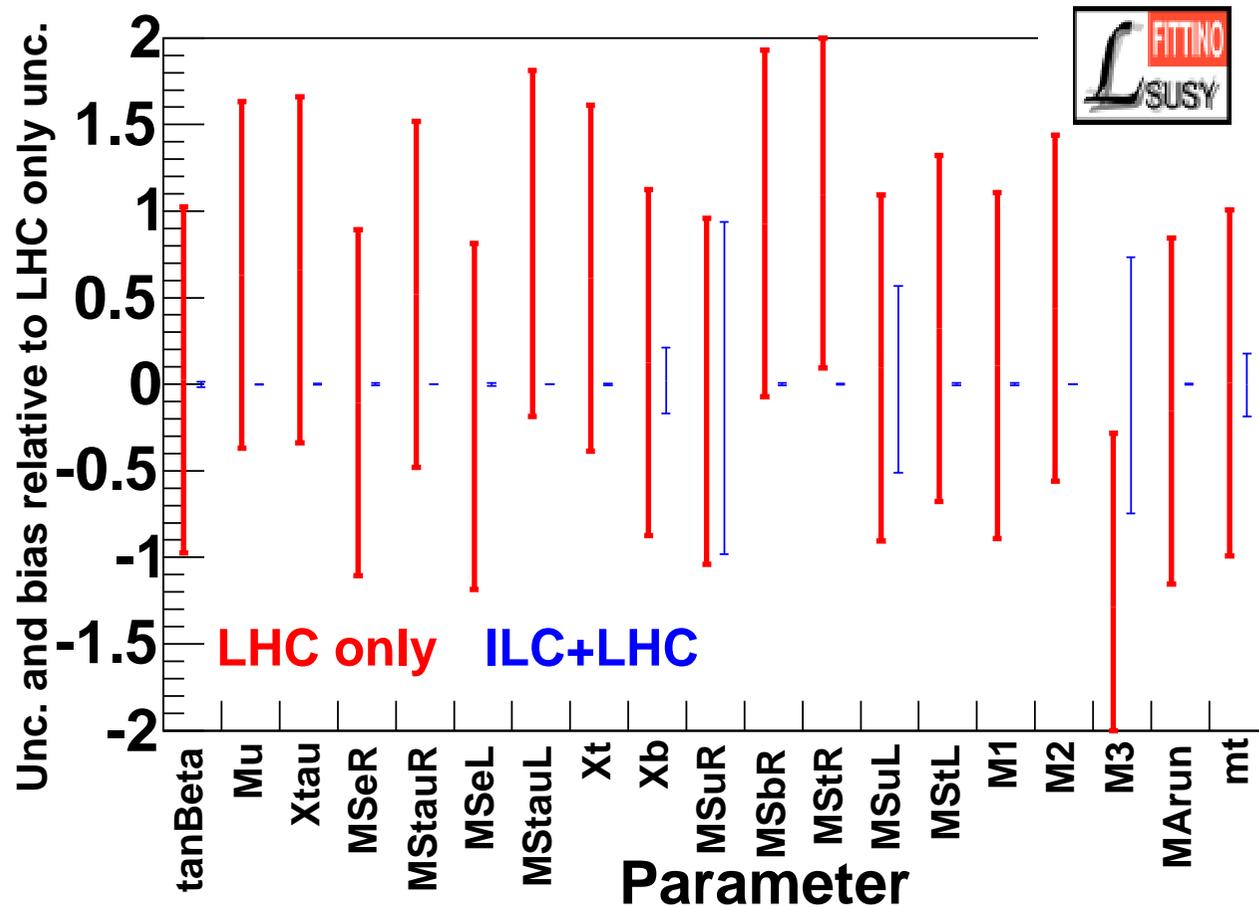


⇒ strong improvement from ILC measurements

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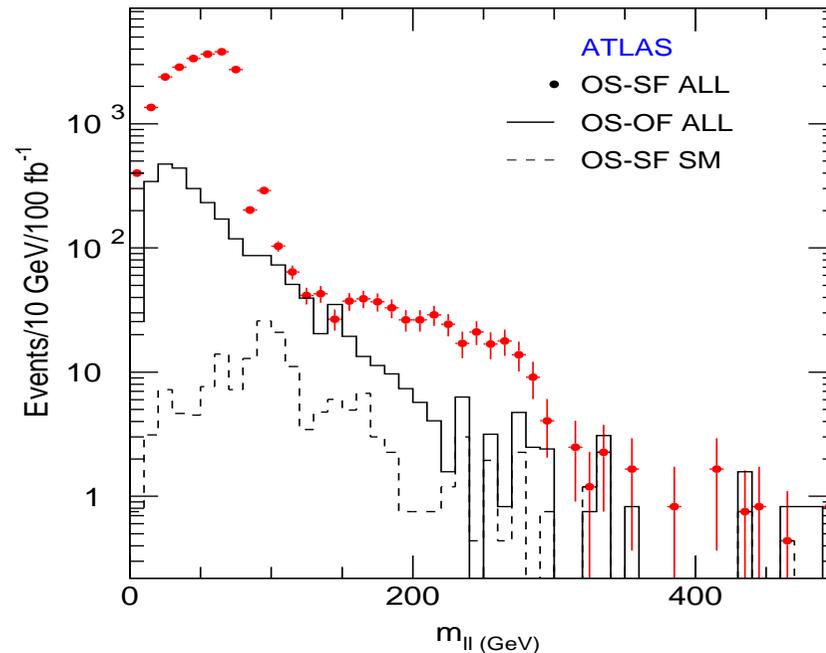


⇒ strong improvement from ILC measurements

One step further:

Determination of the mass of the heaviest neutralino at the LHC using ILC input from the neutralino/chargino sector:

[J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '03]



⇒ Need besides LSP mass also masses of sleptons and charginos from ILC in order to correctly identify $\tilde{\chi}_4^0$

⇒ Feeding $m(\tilde{\chi}_4^0)$ back into ILC analysis improves accuracy of parameter determination at the ILC

Example (II): Indirect determination of \tilde{t} parameters:

Combination of LHC data on heavy Higgs states with ILC data on the light \mathcal{CP} -even Higgs

[K. Desch, E. Gross, S.H., G.Weiglein, L. Zivcovic '04]

Scenario: SPS 1b

⇒ Assume:

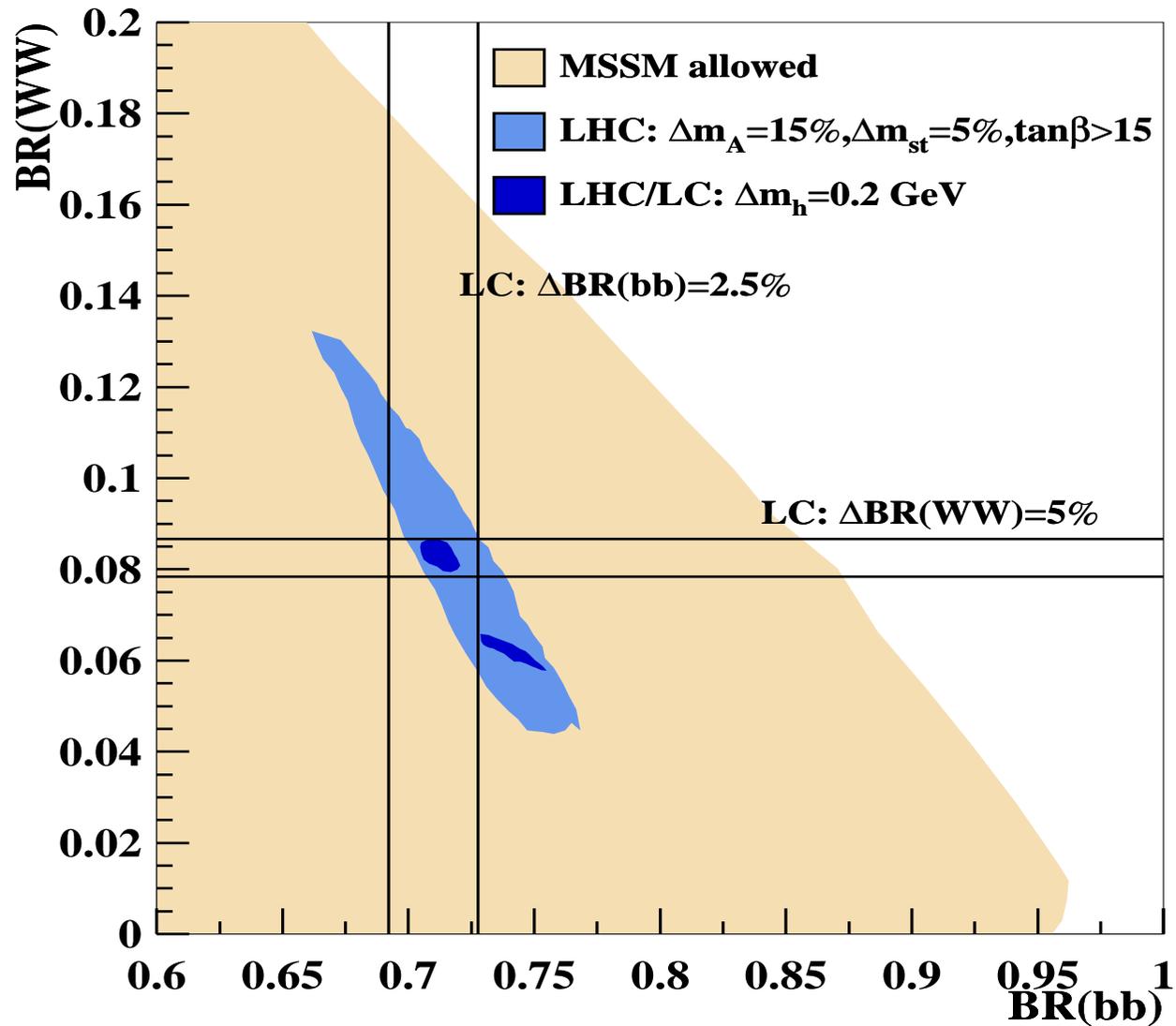
- LHC information on M_A , $\tan\beta$
- ⊕ (LHC ⊗ ILC) information on \tilde{t}/\tilde{b} masses
- ⊕ LHC / ILC measurement of m_h :

M_A : 15% accuracy,

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{b}_1}, m_{\tilde{b}_2}$: 5% accuracy,

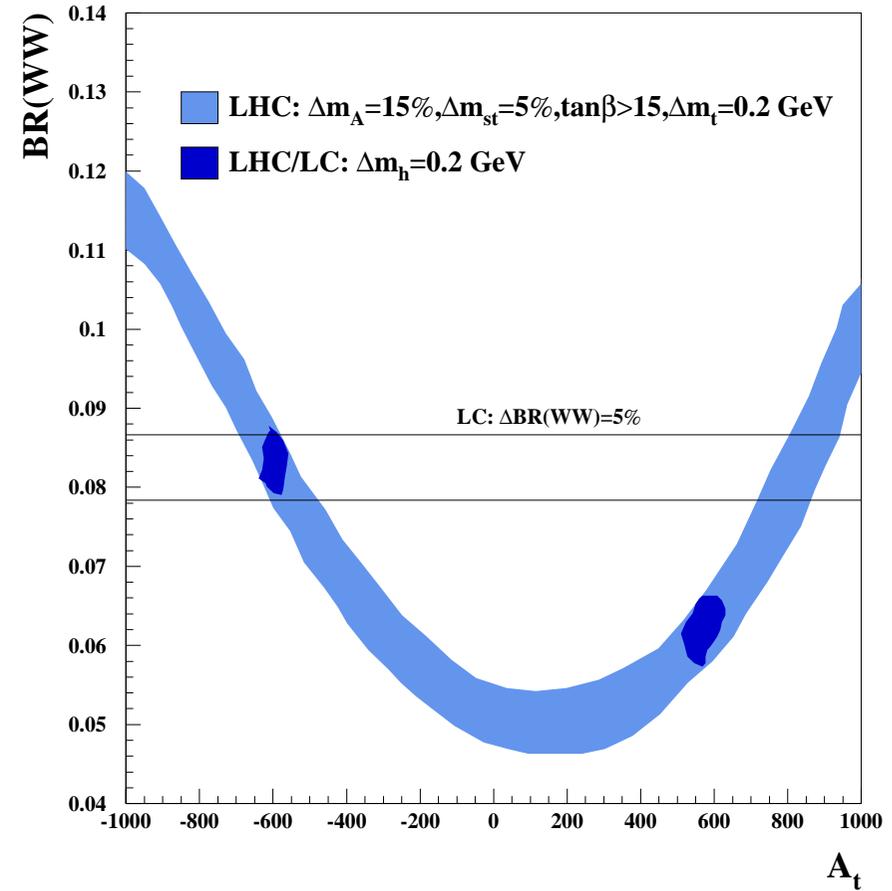
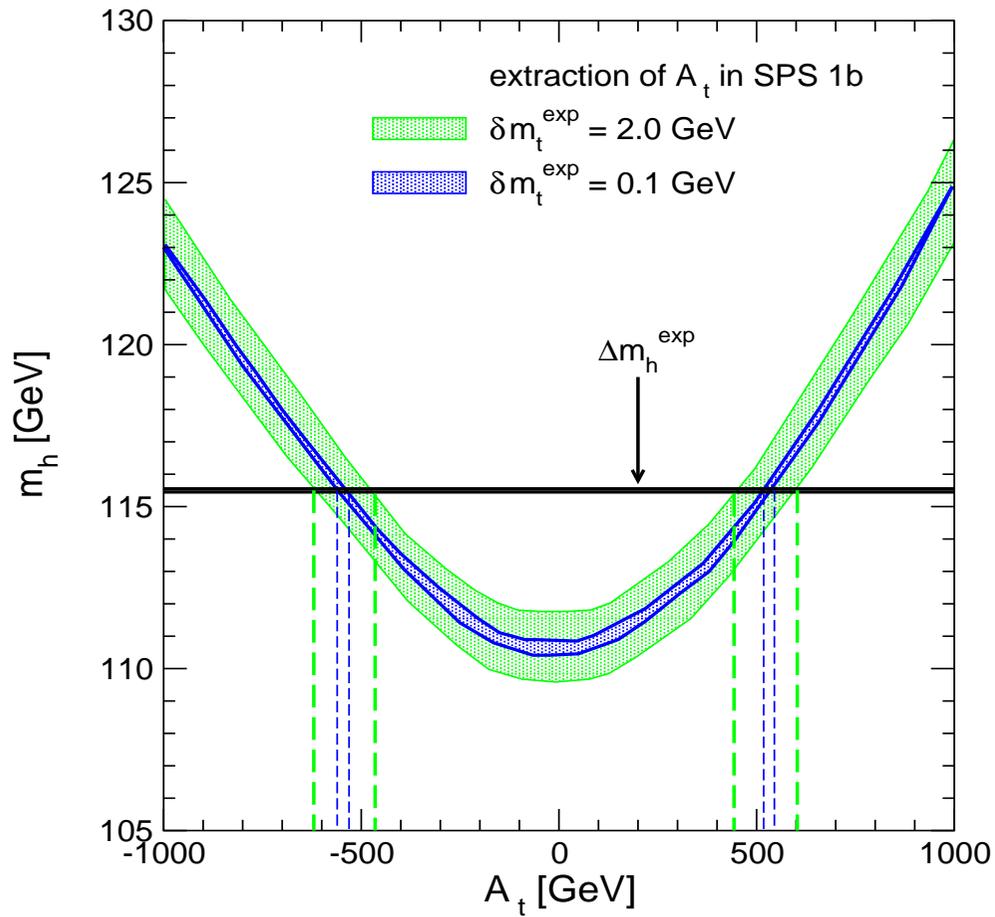
$\tan\beta > 15$

$\text{BR}(h \rightarrow b\bar{b})$: 2.5% accuracy, $\text{BR}(h \rightarrow WW^*)$: 5% accuracy



⇒ Comparison of MSSM prediction based on assumed inputs with BRs measured at the ILC yields very sensitive test of the model

⇒ Indirect determination of trilinear coupling A_t :



Precise measurement of m_t at the ILC crucial, $\delta m_t \lesssim 100 \text{ MeV}$

Δm_t^{ILC} vs. $\Delta m_t^{\text{LHC}} \Rightarrow$ accuracy of A_t determination improved by factor 3

Necessary improvements in accuracy of theoretical prediction in order to match experimental precision at LHC, $\delta m_h^{\text{exp}} \approx 0.2 \text{ GeV}$:

- Uncertainty from experimental errors of input parameters:

⇒ Complementarity example:

In order to match

experimental precision at LHC, $\delta m_h^{\text{exp}} \approx 0.2 \text{ GeV}$

need

ILC precision on m_t , $\delta m_t^{\text{exp}} \lesssim 0.2 \text{ GeV}$

- Uncertainty from unknown higher-order corrections:

⇒ Need improvement by more than a factor 10!

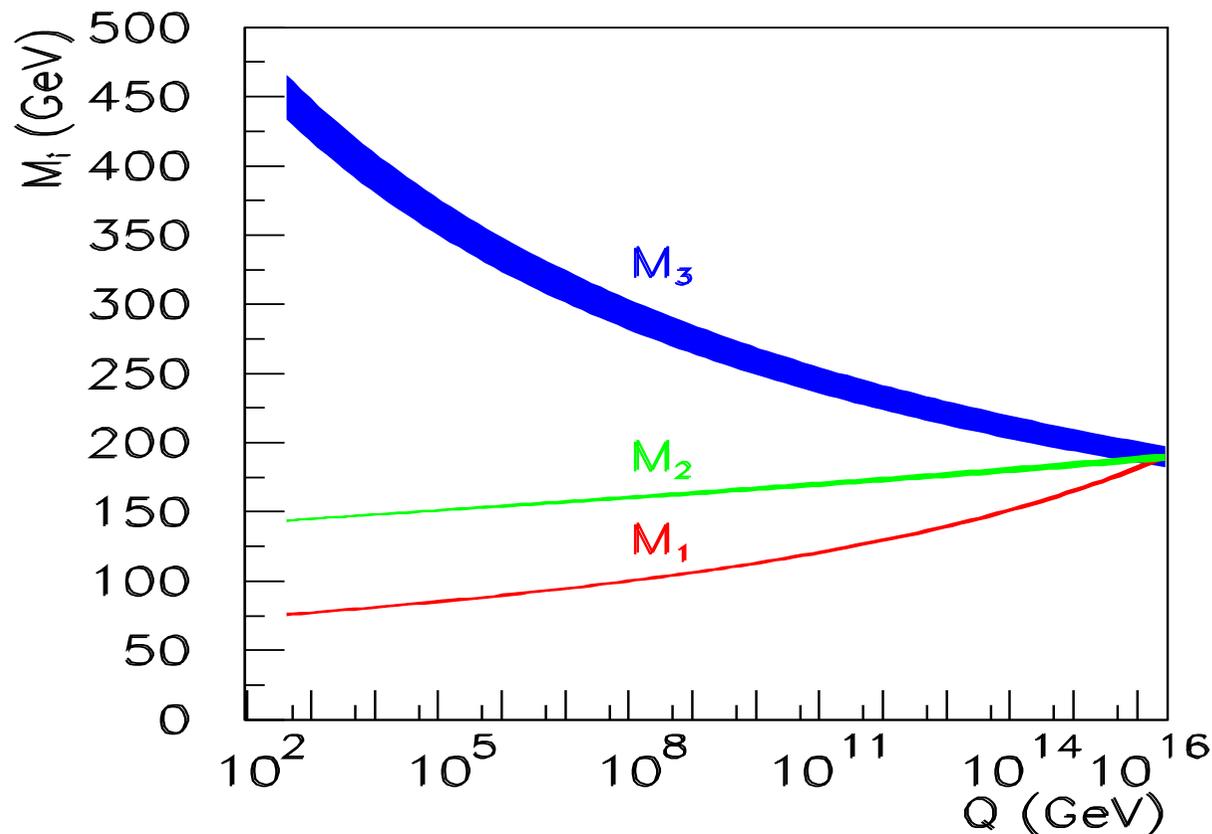
LHC/ILC synergy example (III):

If all low-energy parameters are known: **Extrapolation to high scales**

from combination of LHC and ILC results, precise measurement of masses of SUSY particles, couplings

E.g.: Test of gaugino mass unification

[G. Blair, W. Porod, P. Zerwas '01]



6. Conclusinos

- ILC: linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV, start: 2015(?)
- Top and electroweak precision observables:
 - ⇒ sure physics case for the ILC
 - ⇒ only the ILC precision can point towards (kinematically inaccessible) new physics scales
- – Higgs mechanism is the most attractive solution for EWSB
- – SUSY is the most attractive extension of the SM
- Higgs:
 - theory free coupling measurement possible, $\mathcal{O}(\%)$
 - LHC SUSY Higgs physics needs ILC top precision
- SUSY:
 - mass measurements at the per-cent/per-mille level
 - global fit: drastic improvement from LHC to LHC \oplus ILC

7. Interested in Theory Predictions?

Interested in

- theory predictions for the Tevatron?
- theory predictions for the LHC?
- theory predictions for the ILC?
- phenomenology analyses in Higgs/SUSY?

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⇒ You can do your PhD here at IFCA

contact: Sven.Heinemeyer @ cern.ch